ABSTRACT

Title of Document:	THE INTERRELATIONSHIPS BETWEEN DISSOLVED OXYGEN AND RECREATIONAL *MORONE SAXATILIS* (STRIPED BASS) CATCH IN THE CHESAPEAKE BAY
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Declining dissolved oxygen (DO) conditions in the Chesapeake Bay negatively affect human uses of the Bay, including recreational striped bass fishing. These changes impact where, when, and if fishermen will catch a fish. Development of human-use indicator models allow for more precise quantification of low DO's effect on catch. In this study, improved modeling determined optimum DO for striped bass recreational catch in the Chesapeake to be in the range of 8-9 mg/L. Positive relationships between increased DO and catch were seen in the majority of statistical analysis for the Chesapeake. When DO is increased from 2 to 5 mg/L DO over the whole Chesapeake Bay, there is a corresponding increase in striped bass catch of 149.4%. Results from this study and others demonstrate that not only do human

activities impact the form and function of ecosystems, but the use and enjoyment of those ecosystems by humans is also impaired.

THE INTERRELATIONSHIPS BETWEEN DISSOLVED OXYGEN AND RECREATIONAL *MORONE SAXATILIS* (STRIPED BASS) CATCH IN THE CHESAPEAKE BAY

By

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Table of Contents

Acknowledgements ii
Table of Contents iii
List of Tables iv
List of Figures v
Introduction 1
Study Site Description 3
Methods 7
Data Sources and Preparation 7
Fish Catch Data 7
Water Quality Data 9
Data Analysis and Statistical Methods 13
Results 22
Model Results 22
Non-parametric Results 25
Chesapeake Bay 26
Upper Bay 36
Middle Bay 39
Lower Bay 46
Patuxent River 52
Potomac River 52
Discussion 52
Model Results 52
Non-parametric Results 55
Conclusions and Recommendations 62
References 64

List of Tables

Table 1. Summary of the number of water quality records for each region and subset.

Table 2. Results for the three types of non-parametric statistical test for each region and data subset.

Table 3. Modeled parameter estimates and their significance at the 95th percentile for each region of study in the Chesapeake Bay.

Table 4. DO parameter estimates for nominal logistic regression model results and corresponding R-square values.

Table 5. DO parameter estimate results with corresponding p-values for the Poisson regression model for each region of the Bay.

Table 6. Number of rows of data for statistical analysis by region and water quality group.

Table 7. Striped bass expected fish catch (per angler per trip) results at mean and predictive conditions.

Table 8. Summary of non-parametric DO cluster and frequency analysis with the No Catch class included and excluded.

List of Figures

Figure 1. Examples of point sampling data and interpolated data used for this study.

Figure 2. Chesapeake Bay airshed with watershed.

Figure 3. Map of Chesapeake Bay area and sub-regions.

Figure 4. Point water quality sampling locations and fish survey intercept locations.

Figure 5. Dissolved oxygen distribution for the Chesapeake Bay for all DO means and for each data subset.

Figure 6. Example of One-way ANOVA means analysis results for the Middle Bay sub-region.

Figure 7. Untransformed total striped bass catch clustering and $(\log_{10}) + 1$ transformed total striped bass catch clustering.

Figure 8. Examples of contingency table and correspondence analysis for Cluster analysis for all water quality in the whole Chesapeake Bay.

Figure 9. Examples of contingency table analysis and correspondence analysis for the Middle Bay for the 25th quartile water quality values.

Figure 10. Correspondence analysis for Chesapeake Bay all DO Clusters vs. Catch Clusters with the No Catch class included and excluded.

Figure 11. Correspondence analysis for Chesapeake DO^2 Clusters vs. Catch Clusters with the No Catch class included and excluded.

Figure 12. Correspondence analysis for Chesapeake Bay Lower 10th DO Clusters vs. Catch Clusters with the No Catch class included and excluded.

Figure 13. Correspondence analysis for Chesapeake Bay Lower 25th DO Cluster vs. Catch Clusters with the No Catch class included and excluded.

Figure 14. Correspondence analysis for Chesapeake Bay Lower 10th DO Frequency Clusters vs. Catch Clusters with the No Catch class included.

Figure 15. Correspondence analysis for the Chesapeake Bay Lower 25th DO Frequency Clusters vs. Catch Clusters with the No Catch class included and excluded.

Figure 16. Nominal logistic regression for the Chesapeake Bay for all DO and DO^2.

Figure 17. Nominal logistic regression for the Chesapeake Bay Lower 10th DO.

Figure 18. Correspondence analysis for Upper Bay all DO Clusters vs. Catch Clusters with the NO Catch class included and excluded.

Figure 19. Correspondence analysis for Upper Bay DO^2 Clusters vs. Catch Clusters with the No Catch class included and excluded.

Figure 20. Correspondence analysis for the Middle Bay all DO Clusters vs. Catch Clusters with the No Catch class included.

Figure 21. Correspondence analysis for the Middle Bay DO^2 Clusters vs. Catch Clusters with the No Catch class included.

Figure 22. Correspondence analysis for Middle Bay Lower 10th DO Clusters vs. Catch Clusters with the No Catch class included and excluded.

Figure 23. Correspondence analysis for Middle Bay Lower 25th DO Clusters vs. Catch Clusters with the No Catch class included and excluded.

Figure 24. Correspondence analysis for Middle Bay Lower 10th DO Frequency vs. Catch Clusters with the No Catch class included and excluded.

Figure 25. Correspondence analysis for Middle Bay Lower 25th DO Frequency vs. Catch Clusters with the No Catch class included.

Figure 26. Nominal logistic regression for the Middle Bay for all DO, DO^2, and Lower 25th DO.

Figure 27. Correspondence analysis for Lower Bay all DO Clusters vs. Catch Clusters with the No Catch class included and excluded.

Figure 28. Correspondence analysis for Lower Bay DO^2 Clusters vs. Catch Clusters with the No Catch class included and excluded.

Figure 29. Nominal logistic regression for the Lower Bay for all DO and DO^2.

Figure 30. Map of dissolved oxygen concentrations for July 2006 in the Chesapeake Bay.

Introduction

Degraded dissolved oxygen (DO) conditions in the coastal US including the Chesapeake Bay have been increasing since the early 20th century (Boesch and Brinsfield 2000; Diaz and Rosenberg 1995). Hypoxic and anoxic trends in the Chesapeake Bay over this time period have expanded from the deeper mid and lower channel regions up into the upper Bay and some of the major tributaries, including the Patuxent and Potomac rivers (CPB 1994; Kuo and Neilson 1987; Officer et al. 1984; Simon 1984; Taft et al. 1980; Tuttle et al. 1987). This pervasive low DO problem, which stems from anthropogenic sources of nutrients, has wide ranging impacts for the marine environment including loss of habitat (Boesch et al. 2001), changes in growth and feeding in marine organisms (Dauer et al. 1992; Van der Oost et al. 2003), and changes in marine diversity (Dauer et al. 1992).

Low DO and other secondary results of nutrient inputs and eutrophic conditions in turn significantly affect human uses of coastal waterbodies, including negative impacts to recreational fishing (Bricker et al. 2006; Massey et. al. 2006), human health (Anderson et al. 2000), and boating (Lipton and Hicks 1999; Lipton and Hicks 2003). For recreational fishing, low DO causes changes in fish distribution (Bricker et al. 2006) and feeding habits (Van der Oost et al. 2003) which impact where, when, and if fishermen catch fish.

Traditionally, the study of water quality degradation focuses on how human activities affect coastal water quality. However, there has recently been increased interest in the inverse relationship: how water quality affects human uses of coastal waters and estuaries (US EPA 2005). Researchers have tried to quantify, analyze, and predict the effect of water quality on human uses of coastal waters through the use of indicators (Bricker et al. 2006; Lipton and Hicks 1999; Lipton and Hicks 2003; Massey et al. 2006). These human-use indicators serve to describe a portion of the overall effect that degraded water quality have on human uses of coastal waters.

The extent of the impact of low DO on recreational fishermen in US estuaries was explored by Bricker et al. (2006) through the use of a model that links changes in DO to changes in fish catch. This research also introduced the idea of using this recreational fish catch model to predict fish catch rates within their study region at important DO thresholds. One of the perceived short comings of Bricker et al. (2006) was the use of point water quality to calculate their fish catch rate. An alternate method is the use of interpolated water quality data, which describes more accurately the water quality in a given area (Figure 1).

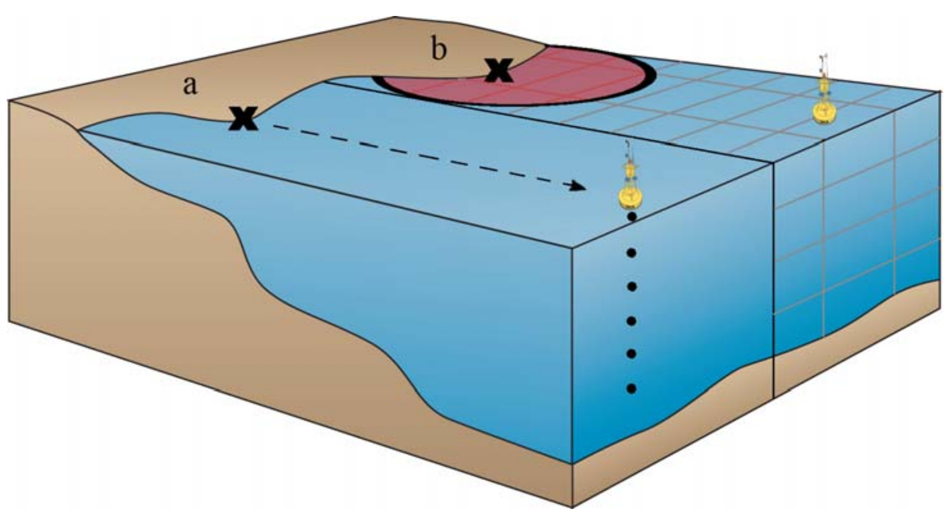


Figure 1. Examples of point sampling data (a) and interpolated data (b) used for this study.

This study recreates the work of Bricker et al. (2006) for the Chesapeake Bay and the Patuxent and Potomac rivers. A human-use indicator, according to Bricker's previous model and based on striped bass catch, is developed using the most recent complete years of data (as of printing time) and using interpolated DO data along with point data. The use of the interpolated DO data, representing DO concentrations covering the entire bay and its tributaries (Figure 1), is hypothesized to better represent water quality conditions where the fisherman likely fished and also allows for the comparison of parameter estimates for both point and interpolated data types to determine if the use of interpolated water quality data is significantly different than the use of point water quality data.

This study also explores both the statistical significance of DO's relationship on recreational fish catch of striped bass (*Morone saxatilis*) observed in the Chesapeake Bay and in what direction is it affecting the catch using one-way analysis of variance (ANOVA), contingency table analysis, and logistic nominal regression.

This improved model allows coastal managers to better determine where resources and further study, pertaining to DO and striped bass, should be allocated in the Chesapeake Bay. Additionally, it can potentially provide fishermen with information, based on DO concentrations, on what regions of the Bay they have the best chance to catch striped bass.

Study Site Description

At over 300 km long with a tidal area of approximately 11,000 km^2, the Chesapeake Bay is the largest estuary in the US. Six states and over 15 million people inhabit the Bay's 167,000 km^2 watershed. The airshed of the Chesapeake Bay includes parts of 15 states and Canada and stretches from South Carolina to above the Great Lakes (Figure 2). Nutrient related impacts within the Bay are well documented (Boesch et al. 2001; Bricker et al. 1999; Dauer et al. 1992; Malone et al. 1993;

Mistiaen et al. 2003; Scavia et al. 2006; Simon 1984; and USEPA 2000a), causing oxygen depletion, increased turbidity, loss of submersed aquatic vegetation, and alteration of food webs. In the last 25 years, the importance of the degradation of coastal and estuarine waters by human related nutrient over-enrichment has become apparent (Malone et al. 1993).

Figure 2. Chesapeake Bay airshed with watershed (inset) (CPB 2008).

In 1983 the multi-state Chesapeake Bay Agreement between the Environmental Protection Agency (EPA), the State of Maryland, the Commonwealths of Pennsylvania and Virginia, and the District of Columbia was signed with the directive to “fully address the extent, complexity, and sources of pollutants entering the Bay”. That original agreement has been updated multiple times since then, with the most recent being in 2000. Clear goals were set for the reduction of nutrients and nutrient related impacts to the bay (USEPA 2000a).

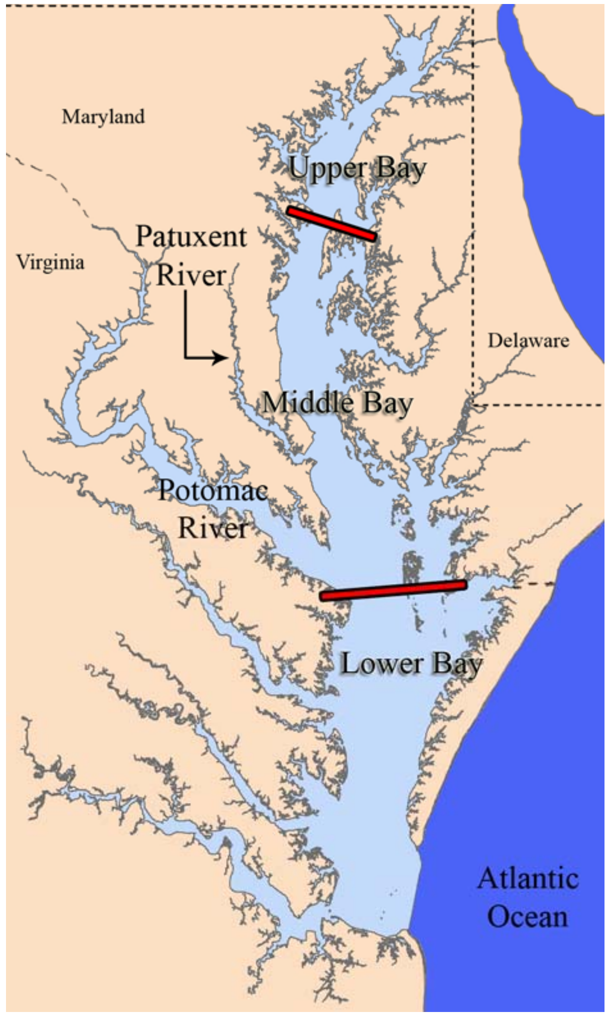


Figure 3. Map of Chesapeake Bay area and sub-regions.

The Chesapeake Bay and its major navigable tributaries were selected for inclusion in this study due to the amount and availability of both water quality data and fish catch data for the region. This study looks at the bay as a whole, as well as selected geographical regions in an attempt to better understand the interrelationships between physical and geographical variability may be having on the fish catch. The regions are the Upper Bay including waters north of the Chesapeake Bay Bridge, the Middle Bay including waters south of the Chesapeake Bay Bridge down to the lower mouth of the Potomac River, the Lower Bay including waters south of the lower mouth of the Potomac River down to the mouth of the Chesapeake Bay, the Patuxent River, and the Potomac River (see figure 3). The Patuxent and Potomac rivers were initially included as sub-regions in this study in order to compare this study's results to the findings of Bricker et al. (2006) but results were not significant for either river by itself.

Striped bass were selected as the indicator species of this study because they are known to be sensitive to changes in water quality (Breitburg et al. 1997; Bricker et al. 2006; Hodson and Hayes 1989; Lipton and Hicks 1999, Lipton and Hicks 2003; Massey et al. 2006). Additional reasons for the selection of striped bass as the indicator species is because they are a heavily targeted fish species by recreational fishermen (ASMFC 2008), and because the species is well studied and the population, as far as overall numbers are concerned, is healthy (Evans and Norton 2000; Sheppard et al. 2005; Welsh et al. 2003; ASMFC 2007; and Cook et al. 2006). Bricker et al. (2006) suggested that the striped bass was the most sensitive of their indicator fish species to DO levels in the water column. Striped bass have the ability to migrate in and out of the Bay and their total population ranges from the St. Lawrence River in Canada all the way down to the St. John's River in Florida (Bigelow and Schroeder 1953). Any decrease in the number of striped bass within an estuary or other semi-enclosed waterbody that is not reflected by a similar decrease in the overall Atlantic population of striped bass is assumed to be caused by specific changes to the striped bass's habitat within the estuary.

Methods

Data Sources and Preparation

Fish Catch Data

Data for striped bass catch were obtained from the National Marine Fisheries Service (NMFS) Office of Science and Technology's (OST) Marine Recreational Inventory Initiative (MRII), formerly known as the Marine Recreational Fisheries Statistical Survey (MRFSS). The MRII program includes collection and archiving of recreational fishing data. The MRII program has been collecting data since 1979 in all coastal states except Texas, Hawaii, Alaska, and U.S. territories (Gray et al. 1994).

MRII data are collected using two different methods: a telephone survey and interviews at fish landing intercept sites. For this study only the data from the intercept site interviews were used for calculating the fish catch totals. The reason for using only the intercept site interviews is because the estimated catch calculated from the intercept interviews is based on the interviewer actually observing catch as well as the close proximity in time to the catch effort. In contrast, telephone interviews can occur at any point after the fishing effort and details are often forgotten. Intercept site interviews are conducted in what are referred to as 'Waves' representing a continuous survey effort conducted by multiple interviewers over a two month period at locations across the US (Gray et al. 1994).

Only intercept sites with interviews that fell within the study area during the 2000-2006 time-period were included in the final analysis (Figure 4). The MRII intercept interview data provide a host of information including, but not limited to, the date and time of the interview, the primary species sought by the angler during the fishing trip, the total number of fish caught of a particular species, the length of time spent fishing, the number of days the angler has gone fishing in the past 12 months, as well as the mode of fishing (e.g. by personal boat, charter boat, from the dock, or from the shore). Only data from fishing trips where striped bass are the primary or secondary species sought by the angler are included. This is because by including only records of striped bass catch where striped bass were targeted helps correct for fisherman avidity or the ability and effort each fisherman puts into catching a fish.

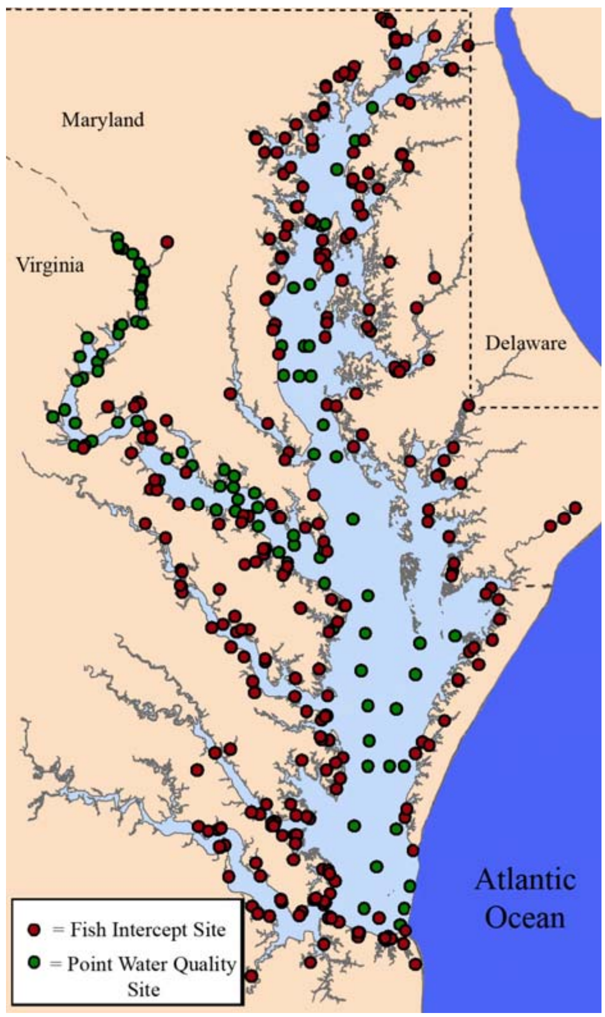


Figure 4. Point water quality sampling locations (green) and fish survey intercept locations (red).

The most recent complete year of available MRII data at the time of this study was for 2006. The total scope of MRII data used in this analysis includes data from January 1, 2000 through December 31, 2006. Total Striped bass catch is calculated from observed catch and released (unobserved) catch respectively. Additional data includes information about the angler, such as hours fished and number of times fished in the last year. These data are used in the model (Equation 1 and Table 3, β_2 and β_3) to correct for fisherman avidity or skill. The final fish catch dataset was comprised of these three groups of data (observed and unobserved catch, and fisherman avidity) merged by a unique identification code variable representing a single fisherman interview.

Water Quality Data

Water quality data used for this analysis came in two parts. Salinity, temperature, and DO point data for the 2000-2006 time period came from the EPA's Chesapeake Bay Program's (CBP) online data hub (CBP 2008), while interpolated DO data, representing 13,000 one meter^2 surface cells and variable additional one meter^2 cells depending on depth at a particular location, were received by direct request (Linker pers. comm. 2007). Interpolated data are calculated by using monitoring data from over 50 stations throughout the Bay and its tributaries. The water quality data at these stations, including water quality measurements down the water column, are combined (with a minimum of four measured values) at fixed distances of one kilometer or less in order to produce a three-dimensional average value for the one meter square cell. The two water quality datasets were merged by date and then parsed out by depth.

DO levels and their effects on Striped bass catch are the basis for this study and lower DO values are of more interest than high ones. This is because Striped bass are sensitive to low DO levels in the water column (Breitburg et al. 1997). Due to the nature of stratification in the bay and its tributaries, the pycnocline plays an important role in oxygen turnover rates and thus the length and severity of low DO events (Baird and Ulanowicz 1989). Because of this, bottom water quality values were separated out from total range of data in order to better capture the complete range of DO (e.g. surface waters tend to have fewer low DO values and thus less variation on which to run statistical analysis). The pycnocline in the Chesapeake was calculated to be at approximately 58% of total depth on average (USEPA 2003). With this guideline, all water quality data below 60% of the total depth was classified as "bottom" water and was subset for use in the study.

DO thresholds used in this study come from NOAA's Estuarine Eutrophication Survey (NOAA 1997). NOAA's DO thresholds are 0 mg/L being anoxic, >0 to 2 mg/L being hypoxic, and >2 to 5 mg/L being a range of biological stress. DO levels above 5 mg/l are not considered problematic and here are given the value of OK. These thresholds are slightly modified for this study from those of 0 mg/L being anoxia to 0-0.5 mg/L being anoxic. The 0-0.5 mg/L classification comes from the EPA's DO criteria (USEPA 2000b). This change to the EPA's anoxic value was made after looking at the DO data distribution for the study region and finding that without changing the threshold, a large number of extremely low DO values would be incorporated into the hypoxic classification. Further modifications were made to the NOAA thresholds with the added classification of DO levels of >5 mg/L to 12 mg/L being considered OK and >12 mg/L and above being classified as high. Additional thresholds for OK were further broken down into values above and below 8 mg/L with values below 8 classified as lower levels of OK and values above 8 classified as the upper levels of OK. 8 mg/L was chosen because the median and mean values of all DO data (approximately 3.4 million interpolated data points) were 8.12 and 8.27 mg/L, respectively. The additional threshold for >12 mg/L was calculated by examining the distribution of DO data and finding that the 90th percentile of bottom water DO fell at 11.68 mg/L for the entire Chesapeake during the 2000-2006 time period.

To better capture the effect of the water quality on striped bass catch, both water quality and fish intercept sites were plotted onto a map of the Chesapeake Bay using a Geographic Information System (GIS). As a proxy for determining the most likely water quality values for the area a given fisherman fished in, 16 km (10 mi) buffers were drawn around each intercept site and only the water quality values inside those buffers were processed. The 16 km buffer was chosen based on two factors, the reported distance fisherman traveled to get to a given fishing site (MRII data), and the average speed and distance typical striped bass fishing boats travel in the Chesapeake Bay (Brown pers. comm. 2008). The MRII distance from landing site data for the 2000-2006 time-period showed that over 90% of fisherman fished within 3 miles of the landing site. It is important to note that a larger number of records lacked distance related data than those that had corresponding distance data. Because of this, a small fishing craft expert was consulted on the average speed and distance traveled by local fishermen and charter boats in the Chesapeake Bay. On average, charter boats travel faster and go farther than personally owned and operated small fishing vessels, but the majority of trips occur within the 16 km buffer. These same buffers were conducted for each sub-region of the Chesapeake Bay as well.

Both datasets (one for water quality and one for fish catch) represented large quantities of data, both in the millions of records. All sub-regions were compared and merged with the same fish catch dataset which represented a total of 2,227,445 records for the entire Chesapeake over the years of 2000-2006. Each sub-region had large water quality datasets associated with them, the largest of which was comprised of 3,390,287 bottom water DO values for the whole Chesapeake region. Table 1 summarizes the number of water quality records for each region.

Region	All Water Qualtiy	25th %	10th %
Chesapeake Bay	3,390,287	847,572	339,029
Upper Bay	454,164	113,541	45,416
Middle Bay	1,544,207	386,052	154,421
Lower Bay	1,487,164	371,791	148,716
Potomac River	1,399,380	349,845	139,938
Patuxent River	614,473	153,618	61,447

Table 1. Summary of the number of water quality records for each region and subset.

Salinity, temperature, and DO values represented the larger of the datasets and required a large amount of processing for eventual combination with the fish catch dataset. The fish catch data represented a set of records at a fixed location (x,y) at date (z), for an individual fisherman (f), but the associated water quality for that x, y, z, and f could entail multiple thousands of water quality values at numerous depths within the 16 km buffer zone. Mean values were taken for salinity, temperature, and DO in order to create the estimate of the water quality at the location where the fisherman fished. This processing inherently removed a large amount of variation from the dataset. To recapture some of the lost variability, means for DO were also calculated using only the lower 10th percentile, and the lower 25th quartile data. Further reasoning behind this data partitioning is explained later.

Water quality data from the CBP was merged with Striped bass catch and fisherman data from the MRII using both SAS and JMP statistical analysis software. The two datasets were merged by location and date with the final dataset being comprised of a unique identification code representing one fisherman's total Striped bass catch on date z (from MRII Types two and three data), information about the fisherman's avidity (Type one data) and the related water quality for the area that he or she fished in (water quality). Each region was subset from this total merged dataset for the entire Chesapeake Bay.

Data Analysis and Statistical Methods

Following Lipton and Hicks (2003) and Bricker et. al. (2006), the expected recreational fish catch was modeled as a function of environmental variables and fisherman-related variables (equation 1).

Equation 1: $C_{f,r} = \alpha + \beta_1 MC_r + \beta_2 HRSF_{f,r} + \beta_3 FDAY_f + \beta_4 BSALIN_r + \beta_5 BTEMP_r + \beta_6 BDO_r + \beta_7 (BDO_r)^2 + \beta_8 (BDO_r * BTEMP_r)$

(Where $C_{f,r}$ is the estimated catch of recreational fisherman f, in area r, representing the sub-regions of the Chesapeake and the Chesapeake as a whole. MC_r is the mean catch of all fishermen fishing in region r. HRSF represents the number of hours spent fishing during the interviewee's recreational fishing trip. FDAY captures the fisherman's skill by showing how many days in the past year the fisherman was out fishing. The environmental variables are characterized by BSALIN, BTEMP, and BDO representing bottom water salinity, bottom water temperature, and bottom water DO respectively. In addition to these environmental variables, BDO was included as a squared term. This is because in quadratic form, the squared term is expected to have a negative coefficient and as such the effect of increased DO on fish catch would decrease with increasing DO concentrations. BDO was also crossed with BTEMP to further explore habitat interaction effects on fish catch.)

Comparison of parameter estimates between the point environmental data and the interpolated environmental data was done following Elton and Greenwood's (1987) comparison of parameter estimates methods through the calculation of the difference of two parameter estimates (Equation 2), and then testing z against Student's t with the degrees of freedom provided by Equation 3.

Equation 2: $z = (b_1 – b_2)/\sqrt{}(s_2^2 + s_2^2)$

(Where s_i is the standard error of the estimate b_i.)

Equation 3: $df = (n_1-2)(n_2-2)\ (s_1^2 + s_2^2)2\ /\ [(n_1-2)s_2^4 + (n_2-2)s_1^4$

(Where n_i is the sample size of the corresponding parameter estimate.)

Nonparametric statistics were also used to examine and describe the relationship between DO and recreational fish catch. Further analysis of the distribution of the data showed that for each sub-region of the bay, the mean bottom water DO level per month rarely dipped below 5 mg/L. With this in mind, further subsets of the data were taken to again try to capture what interactions were occurring during low DO concentrations. These subsets take both the lower 10th percentile and lower 25th quartile of the water quality for each region and then merge them with the fish catch dataset. The result is a set of smaller datasets (fewer matching fish catch records) that inherently favored late spring and summer months when low DO events tend to occur. These subsets of 10th and 25th water quality data showed a more complete range of data over the DO values of interest (0-5 mg/L). Figure 5 shows the interpolated sample site distribution of DO values for the Chesapeake Bay for all DO means, and for each subset.

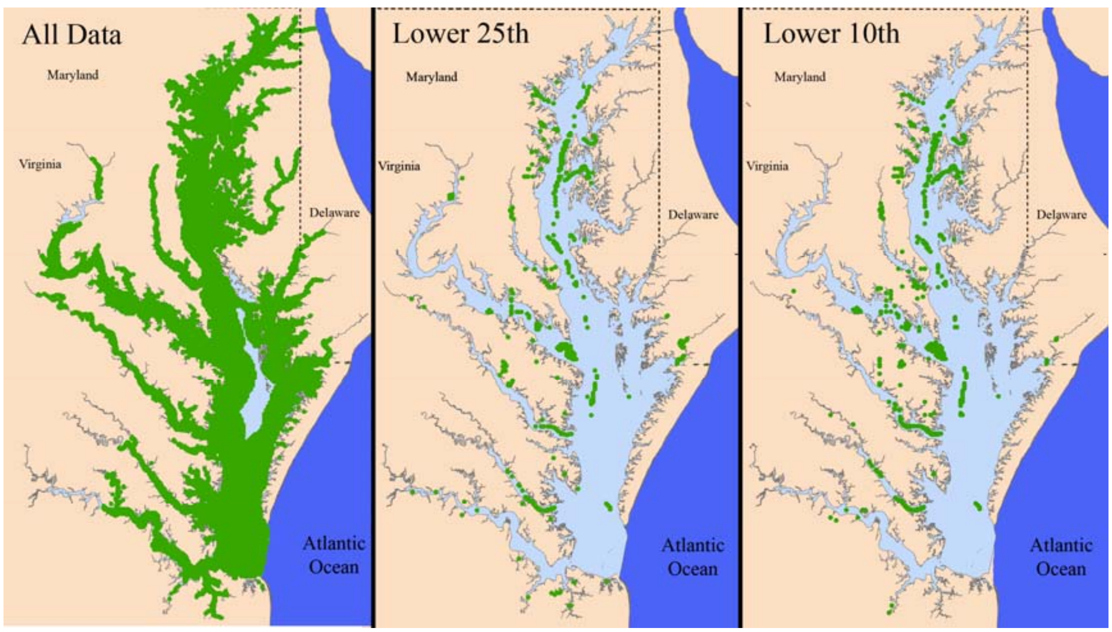


Figure 5. Dissolved oxygen distribution for the Chesapeake Bay for all DO means and for each data subset.

Three main types of statistical analysis were conducted on each region and each subset of data. Cluster analysis was performed for both total catch and DO using contingency table analysis for statistical significance, while cluster and frequency analysis for total catch and DO, respectively, were conducted also using contingency table analysis. Both of these types of analysis are based on Pearson's Chi-squared test. The third type of statistical analysis was nominal logistic regression. All significant results are at minimum *p*-values of <0.05 (Table 2).

Table 2. Results for the three types of non-parametric statistical test for each region and data subset. NLR = Nominal Logistic Regression.

Cluster analysis was conducted by using Ward's agglomerative or hierarchical clustering using JMP where the distances between points is given by equation 4 (JMP 2002). A dendrogram or clustering tree, such as those pictured in Figure 6, are then used to help visually partition the data into roughly equal clusters. Once the clusters have been assigned, one-way ANOVA is used to determine that the means of each resulting cluster are significantly different from each other (Figure 7). The one-way ANOVA tests H_0: $\mu_1 = \mu_2 = \mu_3 = \ldots + \mu_n$, and H_A: That the means are not all equal, at $\alpha = 0.05$ where H_0 is the null hypothesis, H_A is the alternative hypothesis, μ is the population mean, and n is the number of population means being tested. To calculate the variation among sample means, or F-statistic, first the treatment mean square (MSTR), the error sum of squares (SSE), the error mean square (MSE), and treatment sum of squares (SSTR) had to be calculated for the data. Calculation of SSTR, MSTR, SSE, and MSE are given in equations 5 through 8, respectively (Weiss 2004). Calculation of the final F-statistic is given by equation 9.

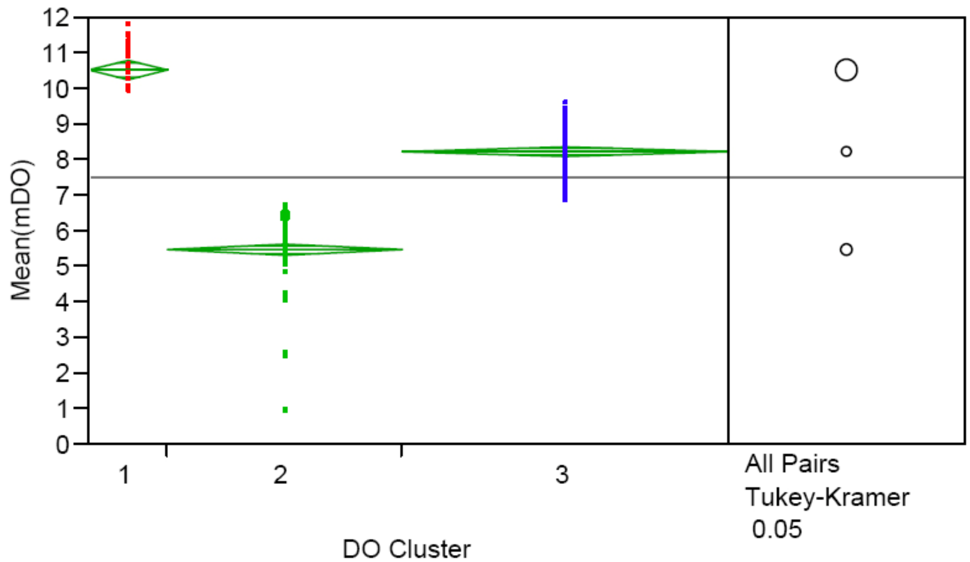


Figure 6. Example of One-way ANOVA means analysis results for the Middle Bay sub-region.

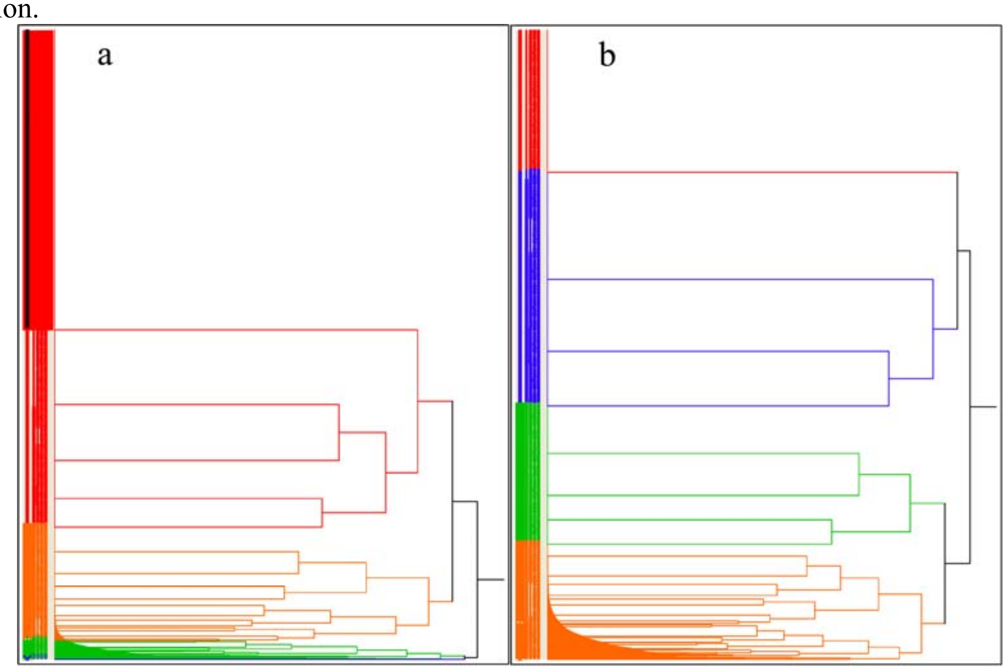


Figure 7. Untransformed total striped bass catch clustering (a) and (log_{10}) + 1 transformed total striped bass catch clustering (b).

Equation 4: $D_{KL} = (||x_K - x_L||^2)/[(1/ N_K)+(1/ N_L)]$

(Where D is the distance between clusters, K and L are the K^{th} or L^{th} cluster (subset of {1, 2,..., n}), $||x_K - x_L||$ is the square root of the sum of the squares of the elements of $x_K - x_L$ (the Euclidean length of the vector $x_K - x_L$), and N is the number of observations.)

Equation 5: $SSTR = n_1(\mu_1 – \mu_x)^2 + n_2(\mu_2 – \mu_x)^2 + \ldots + n_k(\mu_k – \mu_x)^2$

(Where k is the number of clusters, n is the number of rows of data (per cluster), μ_x is the overall population mean given by $\mu_x = \Sigma x/n$, and μ is the cluster mean.)

Equation 6: $MSTR = SSTR/(k – 1)$

Equation 7: $SSE = (n_1 – 1)s_1^2 + (n_2 – 1)s_2^2 + \ldots + (n_k – 1)s_k^2$

(Where s^2 is the sample variance given by $s^2 = \Sigma(x – \mu_x)^2/(n – 1)$.)

Equation 8: $MSE = SSE/(n – k)$

Equation 9: $F = MSTR/MSE$

The means of each cluster were then also compared with each other using Tukey's HSD test ($\alpha = 0.05$). Tukey's HSD compares multiple means of *a* given sample population by calculating two statistics, q and q_s, and gives a final value, *a*, which determines whether the means in question are significantly different from one another (see Equations 10 through 12).

Equation 10: $q = \text{range}/s$

(Where q is the studentized range, range = max – min value of random population sample 1, and s = the standard deviation of random population sample 2.)

Equation 11: $q_s = (Y_A - Y_B)/SE$

(Where Y_A is the largest mean of all available means, Y_B is one of the remaining smaller means, and SE is the standard error of the data.)

Equation 12: $a = (q_s - q)$

If a is a positive number then the means are significantly different. Conversely, if a is a negative number then the means are not significantly different. The resulting one-way analysis plot also allowed for the renaming of the cluster categories into meaningful groups (e.g. high, medium, and low). The $(\log_{10}) + 1$ of the total Striped bass catch were taken in order to facilitate cluster analysis. Transforming the total catch did not normalize the data, but helped to cluster the data into similar groups (Figure 7). By transforming the total striped bass catch via $(\log_{10}) + 1$, a natural byproduct was the creation of a category of total stripe catch with missing values. These missing values denoted where no fish were caught and thus renamed NC for No Catch. This additional class was later used in both DO cluster vs. catch cluster analysis and frequency vs. catch cluster analysis. By either including or excluding this No Catch class, the effect of the dependent DO variable on the independent catch response variable could be examined as an overall effect on the sample, or the effect only when a fish was caught.

DO square values were also analyzed as clusters. This was done because by squaring the DO variable a parabolic variable was created that helps account for perceived decreasing effect of DO at higher concentrations. Where the means of clusters were significantly different from each other, the clusters for both striped bass total catch and DO were then analyzed using contingency tables and correspondence analysis (Figure 8).

a

(log10) + 1 Total Catch

DO Cluster	Count Total % Col % Row %	H	MH	M	ML	L	NC	
	H	68 2.06 21.52 10.64	103 3.11 27.18 16.12	85 2.57 24.43 13.30	64 1.93 21.84 10.02	63 1.90 16.03 9.86	256 7.74 16.21 40.06	639 19.32
	MH	76 2.30 24.05 8.42	99 2.99 26.12 10.96	90 2.72 25.86 9.97	86 2.60 29.35 9.52	110 3.33 27.99 12.18	442 13.36 27.99 48.95	903 27.30
	ML	73 2.21 23.10 8.48	99 2.99 26.12 11.50	83 2.51 23.85 9.64	66 2.00 22.53 7.67	125 3.78 31.81 14.52	415 12.55 26.28 48.20	861 26.03
	L	99 2.99 31.33 10.94	78 2.36 20.58 8.62	90 2.72 25.86 9.94	77 2.33 26.28 8.51	95 2.87 24.17 10.50	466 14.09 29.51 51.49	905 27.36
		316 9.55	379 11.46	348 10.52	293 8.86	393 11.88	1579 47.73	3308

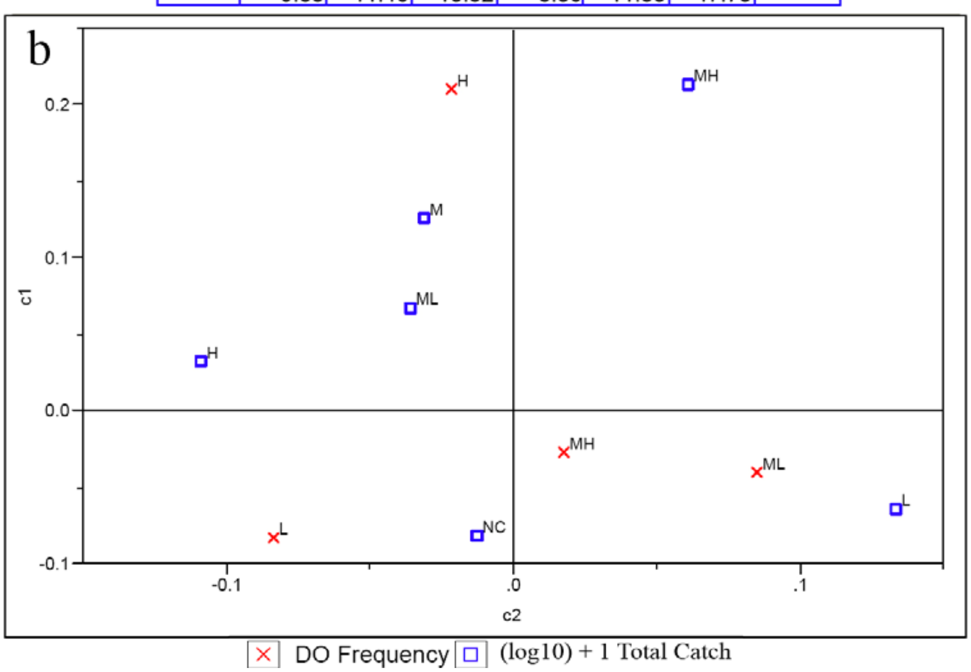


Figure 8. Examples of contingency table (a) and correspondence analysis (b) for Cluster analysis for all water quality in the whole Chesapeake Bay. NC= No Catch, L= Low, ML= Medium Low, MH= Medium High, H= High.

Frequency analysis was conducted by breaking the DO values for a given region or subset into its corresponding classification. As previously discussed, the DO classes used are 0-0.5 mg/l being anoxia, >0.5 mg/L to 2 mg/L being hypoxia, >2 mg/L to 5 mg/L being biological stress (Stress), >5 mg/L to 8 mg/L being Lower levels of OK (LOK), >8 mg/L to 12 mg/L being the Upper levels of OK (UOK), and >12 mg/L being high (SS). These classifications were then compared using contingency tables and correspondence analysis with the previous cluster analysis results for the $(\log_{10}) + 1$ total striped bass catch (Figure 9).

The third method of statistical analysis was nominal logistic regression. Total catch was converted to a new variable called 'catch'. The variable 'catch' describes simply whether striped bass were caught by the fisherman during their trip with either a 0 or a 1 representing the presence or absence of any fish caught, respectively. Using equation 13, 'catch' was regressed against either the mean DO or DO^2 for each region and data subset.

Equation 13: $\ln(p_g/p_1) = \ln(P_g/P_1) + \beta_{g1}X_1 + \beta_{g2}X_2 + \ldots + \beta_{gn}X_n$,

(Where p_g is equal to the probability that an individual with values X_1, X_2, X_n is in group g, P_g equals the prior probabilities of group membership, and β_{gn} equals the population regression coefficients that are to be estimated from the data (JMP 2002).)

a

(log10) + 1 Total Catch

DO Frequency

Count Total % Col % Row %	H	M	L	NC	
Anoxia	20 6.21 33.90 14.29	30 9.32 41.67 21.43	25 7.76 58.14 17.86	65 20.19 43.92 46.43	140 43.48
Hypoxia	9 2.80 15.25 16.98	11 3.42 15.28 20.75	11 3.42 25.58 20.75	22 6.83 14.86 41.51	53 16.46
Stress	30 9.32 50.85 23.26	31 9.63 43.06 24.03	7 2.17 16.28 5.43	61 18.94 41.22 47.29	129 40.06
	59 18.32	72 22.36	43 13.35	148 45.96	322

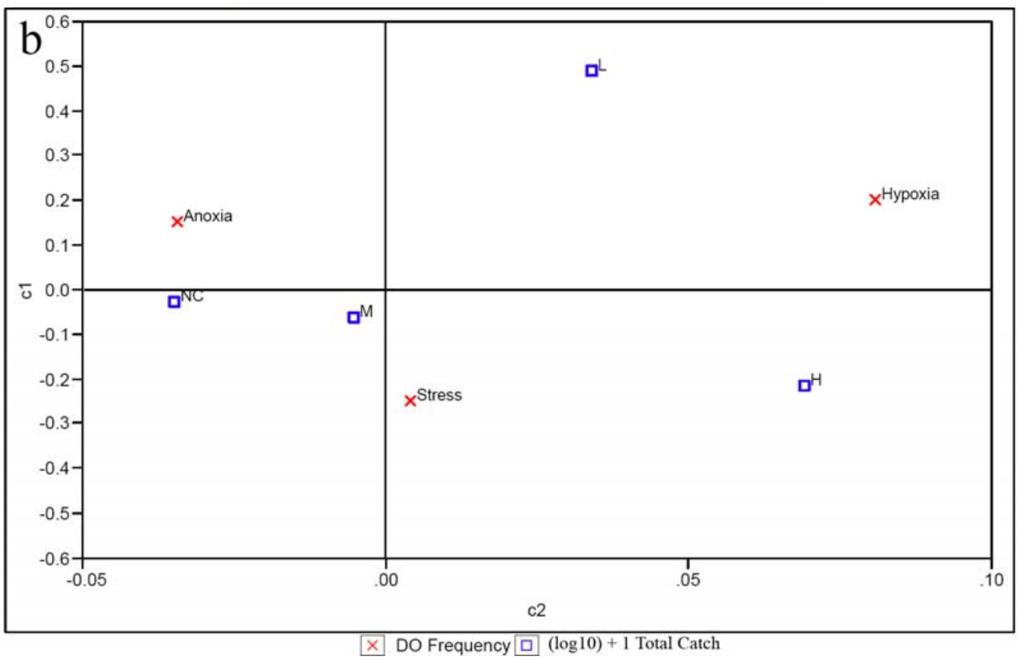


Figure 9. Examples of contingency table analysis (a) and correspondence analysis (b) for the Middle Bay for the 25th quartile water quality values. NC= No Catch, L= Low Catch, M= Medium Catch, H= High Catch.

Results

Model Results

Table 3 shows the modeled parameter estimates and their respective significance for each region studied and for all eight variables included in the model.

	Model R-Square	Mean Catch (β_1)	Hours Fished (β_2)	Days Fished in Previous 12 Months (β_3)	Bottom Salinity (β_4)	Bottom Temperature (β_5)	Bottom Dissolved Oxygen (DO) (β_6)	Bottom DO^2 (β_7)	Bottom DO x Bottom Temperature (β_8)
Abbreviations		**MC**	**HRSF**	**FDAY**	**BSALIN**	**BTEMP**	**BDO**	**BDO^2**	**BDO*BTEMP**
Chesapeake Bay	0.0459	0.3674	0.1379	-0.0001	-0.0042	0.0743	0.8995	-0.0355	-0.0073
Upper Bay	0.1444	0.3747	0.1167	0.0008	-0.0688	0.1736	1.7676	-0.0776	-0.0135
Middle Bay	0.0856	0.3603	0.1201	-0.0004	-0.1038	-0.1482	0.6797	-0.0679	0.0209
Lower Bay	0.0443	0.4564	0.1607	0.0001	-0.0192	-0.0181	-0.0027	-0.0005	0.0011
Patuxent River	0.1825	0.6589	0.2084	0.0005	-0.0509	0.025	-0.9799	0.0800	0.0050
Potomac River	0.1716	0.2527	0.3442	0.0138	-0.4222	-0.8600	-4.3616	0.1680	0.1360

= significant at the 95th percentile

= not significant at the 95th percentile

Table 3. Modeled parameter estimates and their significance at the 95th percentile for each region of study in the Chesapeake Bay.

	Model R-Square	Mean Catch (β_1)	Hours Fished (β_2)	Days Fished in Previous 12 Months (β_3)	Bottom Salinity (β_4)	Bottom Temperature (β_5)	Bottom Dissolved Oxygen (DO) (β_6)	Bottom DO^2 (β_7)	Bottom DO x Bottom Temperature (β_8)
Abbreviations		**MC**	**HRSF**	**FDAY**	**BSALIN**	**BTEMP**	**BDO**	**BDO^2**	**BDO*BTEMP**
Chesapeake Bay All	0.0316	-0.3537	-0.1587	-0.0001	0.0193	0.0730	-0.1522	-0.0076	-0.0045
Chesapeake Bay 10th	0.0255	-0.2331	-0.1761	-0.0001	0.0020	0.0695	-0.1578	-0.0089	-0.0036
Middle Bay All	0.0823	-0.1025	-0.1599	0.0001	0.0592	-0.0663	-0.4328	0.0401	-0.0010
Middle Bay 25th	0.0800	0.0285	-0.1861	0.0003	0.0235	-0.0792	-0.6159	0.0534	-0.0161
Lower Bay All	0.0277	-0.3893	-0.2128	-0.0001	0.0293	0.0137	-0.2276	-0.0091	0.0014

[green] = significant at the 95th percentile

[red] = not significant at the 95th percentile

Table 4. DO parameter estimates for nominal logistic regression model results and corresponding R-square values at the 95th percentile.

Table 4 shows the modeled parameter estimates and their respective significance for the nominal logistic regression analysis for each region that had significant results, while Table 5 shows the DO parameter estimate results for the Poisson regression models for each region of the Bay with their respective p-values. The Patuxent, Potomac, and the Lower Bay did not have significant results for DO during the 2000 to 2006 time period.

Region	DO Parameter Estimate	p-value
Chesapeake Bay	0.8995	<.0001
Upper Bay	1.7676	0.0037
Middle Bay	0.6797	0.0001
Lower Bay	Not significant	0.9925
Potomac River	Not significant	0.1040
Patuxent River	Not significant	0.2376

Table 5. DO parameter estimate results with corresponding p-values for the Poisson regression model for each region of the Bay.

Non-parametric Results

As can be seen in Table 2, significant results for the Upper and Lower Bay, and the Patuxent and Potomac River regions were low, having only three significant tests combined. The Bay as a whole and the Middle Bay both exhibited good response to statistical analysis, having fourteen significant tests between the two regions. Possible reasons for this breakdown of results are addressed later. Table 6 shows the number of rows of data that were used in the calculation of the statistical results.

Region	All WQ	25% WQ	10th% WQ
Chesapeake Bay	3308	2790	1603
Upper Bay	356	347	284
Middle Bay	389	351	295
Lower Bay	1827	886	315
Potomac River	186	110	85
Patuxent River	62	50	45

Table 6. Number of rows of data for statistical analysis by region and water quality (WQ) group.

Chesapeake Bay

Cluster analysis was conducted on all water quality data for the variables mean DO and the ($\log_{10}$) + 1 of total striped bass catch (from here on simply called catch) for the Chesapeake Bay region. The means of each of the clusters for all of the Chesapeake for both variables were statistically significant from the others using Tukey's HSD. Based on the ANOVA means the clusters were assigned the names Low (L), Medium Low (ML), Medium High (MH), and High (H) for both DO and DO^2 and Low (L), Medium Low (ML), Medium (M), Medium High (MH), High (H), and No Catch (NC) for catch. Figure 10 shows the correspondence analysis plots for DO vs. catch with and without the "No Catch" class. The Chi squared probability for contingency table for the two clusters with the "No Catch" class included was <0.0001 and the R-squared value was 0.0051, while the Chi squared probability without the "No Catch" class was 0.0026 and the R-squared value was 0.0054.

The correspondence analysis of DO clusters vs. catch clusters with the "No Catch" class included appeared to show that for the whole Chesapeake Bay region that medium low (ML), medium (M), and high (H) catch corresponded with high (H) DO, that low (L) catch corresponded with medium low (ML) and medium high (MH)

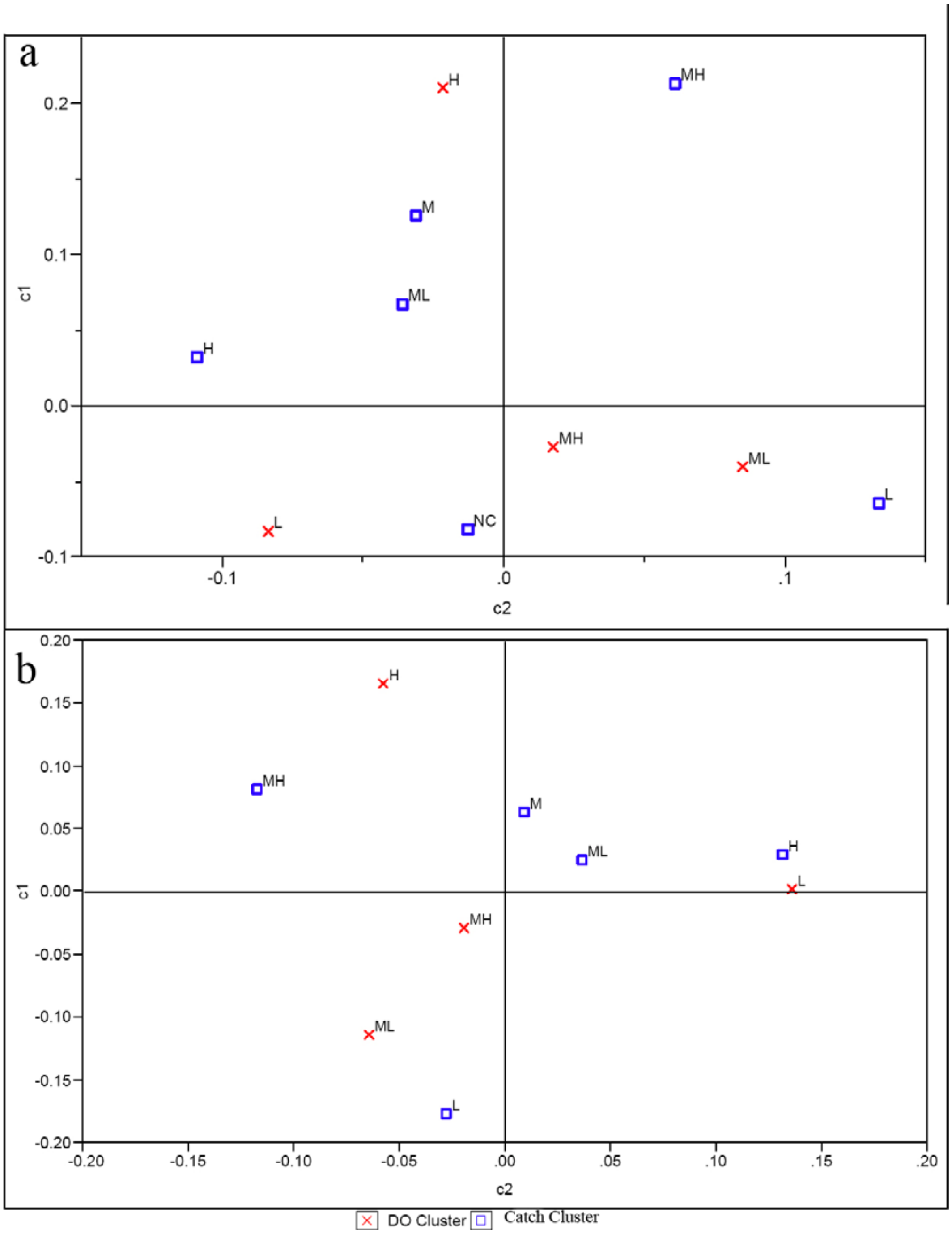


Figure 10. Correspondence analysis for Chesapeake Bay all DO Clusters vs. Catch Clusters with the No Catch class (NC) included (a) and excluded (b). NC= No Catch, L= Low, ML= Medium Low, M= Medium, MH= Medium High, H= High.

DO, and that No Catch (NC) was corresponded to low DO (Figure 10a). Medium high catch did not appear to correspond with the other clusters. The correspondence analysis of DO clusters vs. catch clusters with the "No Catch" class excluded appeared to show that low catch corresponded to medium low and medium high DO, that medium low, medium, and high catch corresponded to low DO, and that medium high catch corresponded to high DO (Figure 10b).

Cluster analysis was also conducted on the square of the mean DO. The DO^2 means were significantly different from each other using Tukey's HSD and the resulting statistics for "No Catch" included and excluded were Chi squared probabilities of <0.0001 and 0.0134, respectively, and R-squared values of 0.0044 and 0.0035, respectively.

The correspondence analysis of DO^2 clusters vs. catch clusters with the "No Catch" class included appeared to show that "No Catch" corresponded to low DO, that low catch corresponded to medium DO, and that medium and high catch corresponded to high DO (Figure 11a). The correspondence analysis of DO^2 clusters vs. catch clusters with the "No Catch" class excluded appeared to show that low catch corresponded to medium DO, that medium catch corresponded to low DO, and that high catch corresponded to high DO (Figure 11b).

The cluster analysis for the same variables as above was also conducted on the lower 10^{th} percentile and lower 25^{th} percentile water quality datasets. The means of all clusters for both the lower 10^{th} and 25^{th} percentiles were all significantly different from each other. Only the mean DO clusters were significant for the contingency and correspondence analysis for the lower 10^{th} percentile. The resulting statistics for the "No Catch" class included and excluded were Chi squared probabilities of <0.0001 and 0.0004, respectively, and R-squared values of 0.0094 and 0.0142, respectively. Like the lower 10^{th} percentile, the lower 25^{th} percentile water quality contingency and correspondence analysis, only the mean DO clusters were significant. The resulting statistics for “No Catch” included and excluded were Chi squared probabilities of 0.0098 and 0.0404, respectively, and R-squared values of 0.0024 and 0.0032, respectively.

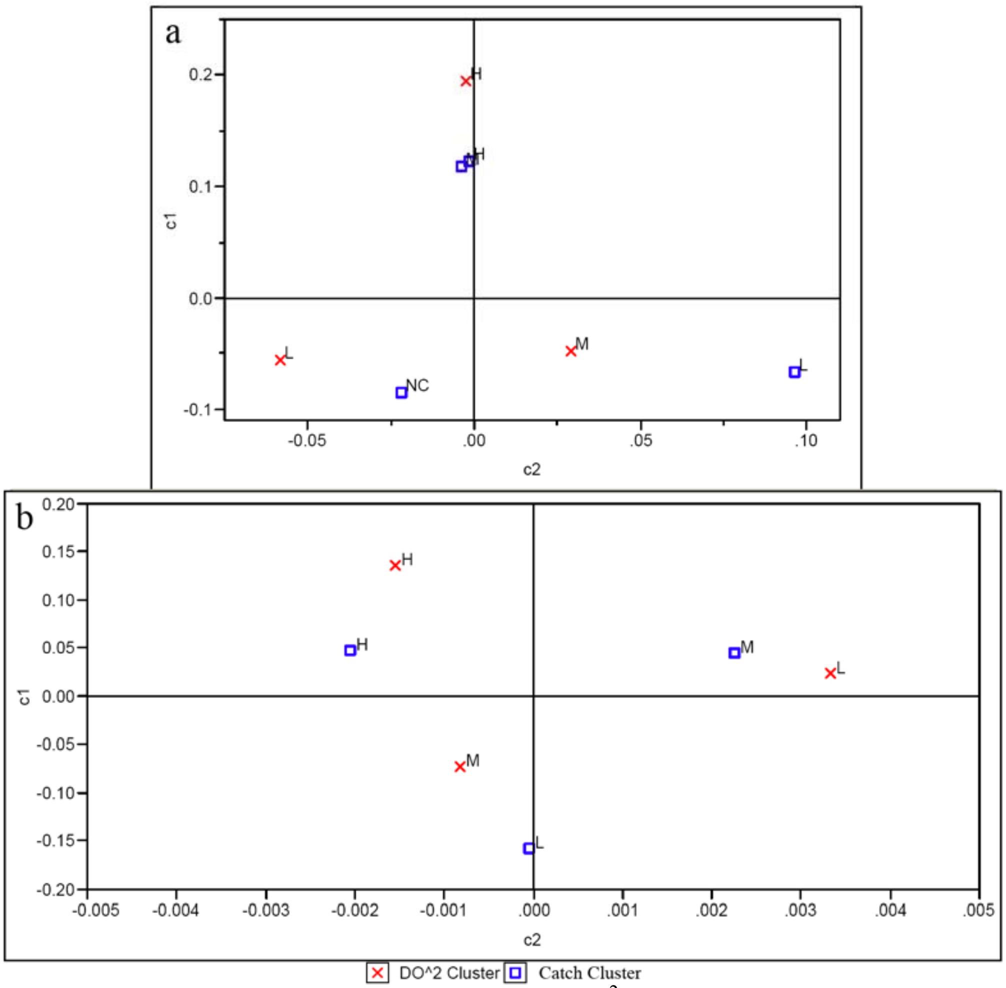


Figure 11. Correspondence analysis for Chesapeake DO^2 Clusters vs. Catch Clusters with the No Catch class (NC) included (a) and excluded (b). NC= No Catch, L= Low, M= Medium, H= High.

Correspondence analysis of DO clusters vs. catch clusters with the “No Catch” class included for the lower 10th percentile water quality appeared to show that low catch corresponded to medium low DO, and that no catch and medium high catch corresponded to medium high and high DO. Medium low and high catch and low DO did not appear to correspond with any clusters of the opposite type (Figure 12a). The correspondence analysis of DO clusters vs. catch clusters with the "No Catch" class excluded for the lower 10th percentile water quality appeared to show that low catch corresponded to medium low DO, that medium low and medium high catch corresponded to medium high and high DO, and that high catch corresponded to low DO (Figure 12b).

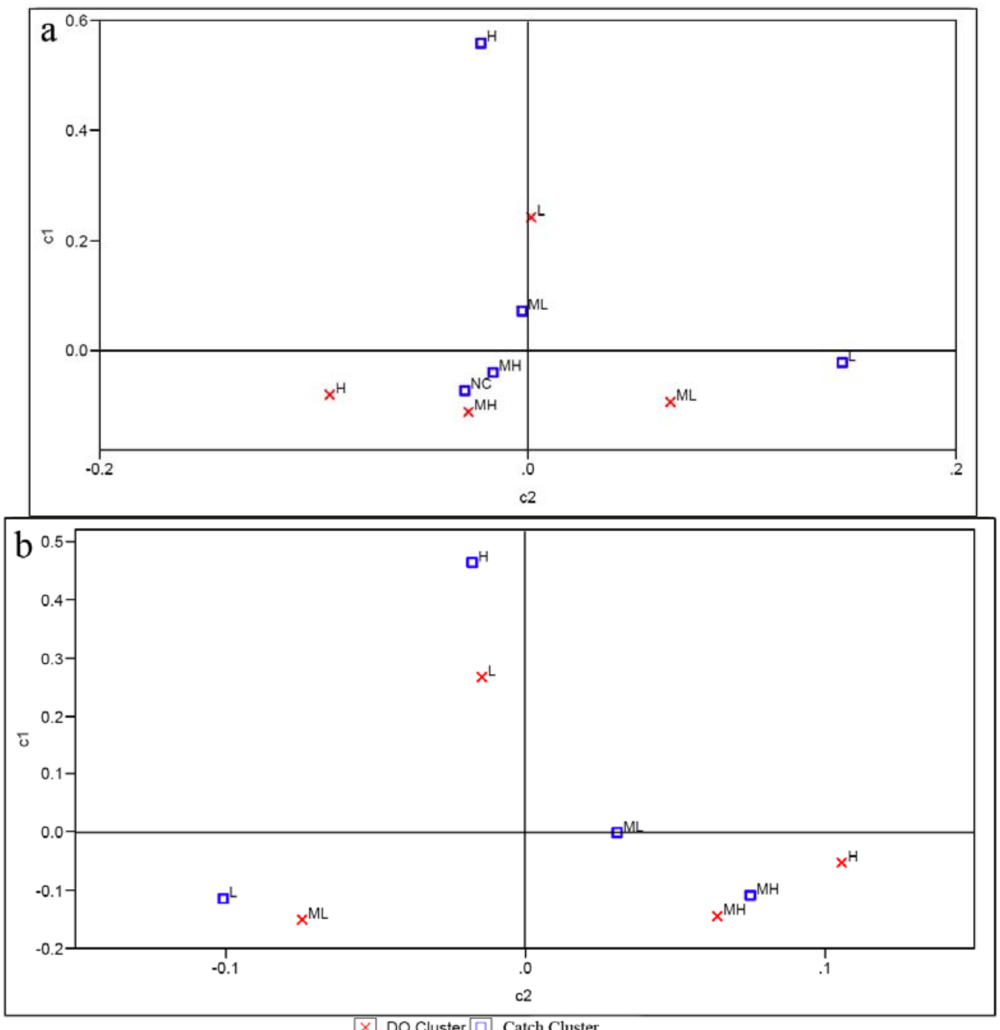


Figure 12. Correspondence analysis for Chesapeake Bay Lower 10th DO Clusters vs. Catch Clusters with the No Catch class (NC) included (a) and excluded (b). NC= No Catch, L= Low, ML= Medium Low, MH= Medium High, H= High.

Correspondence analysis of DO clusters vs. catch clusters with the "No Catch" class included for the lower 25th percentile water quality appeared to show that no catch corresponded to medium high DO, that medium catch corresponded to high DO, and that high catch corresponded with low DO. Low catch did not appear to correspond to any DO cluster (Figure 13a). Correspondence analysis of DO clusters vs. catch clusters with the "No Catch" class excluded appeared to show that medium catch corresponded to high DO and that high catch corresponded to low DO (Figure 13b). Low catch and medium high DO did not appear to correspond to any other clusters.

DO frequency vs. catch cluster contingency and correspondence analysis for the entire Chesapeake region was only significant for the 10th and 25th percentile water quality datasets (Table 2). For the 10th percentile the resulting statistics for the "No Catch" class included were a Chi squared probability of 0.0013, and an R-squared value of 0.0054. Results for the "No Catch" class excluded were not significant. The resulting statistics for the lower 25th percentile for the "No Catch" class included and excluded were Chi squared probabilities of 0.0007 and 0.0144, respectively, and R-squared values of 0.0040 and 0.0051, respectively.

Correspondence analysis for DO frequency vs. catch cluster for the lower 10th percentile water quality data with the "No Catch" class included appeared to show that no catch corresponded to DO stress, low catch corresponded to hypoxia, and high catch corresponded to anoxia (Figure 14). Medium catch did not appear to correspond with any DO frequency. Correspondence analysis for the lower 10th percentile was not statistically significant.

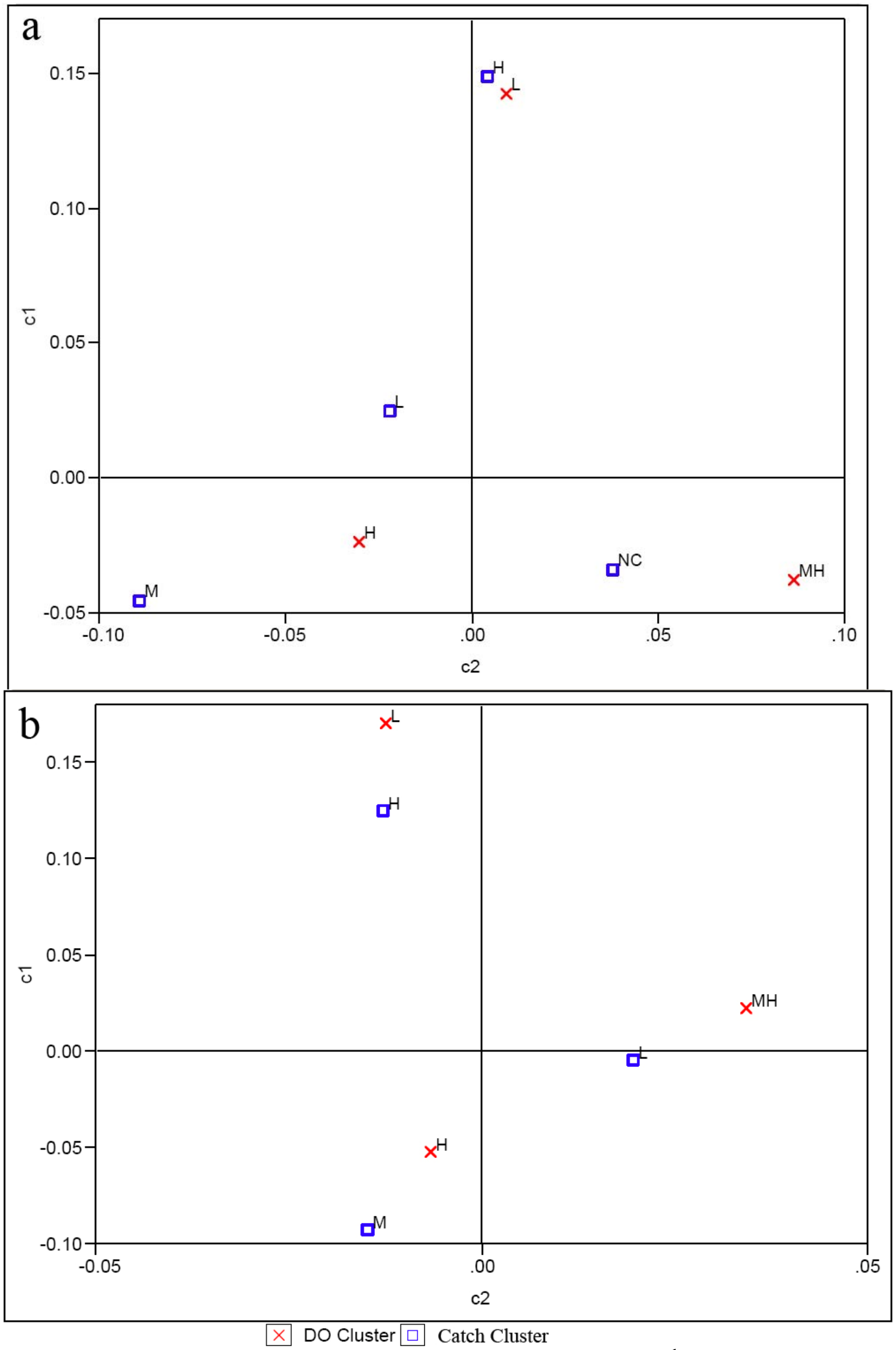


Figure 13. Correspondence analysis for Chesapeake Bay Lower 25th DO Cluster vs. Catch Clusters with the No Catch class (NC) included (a) and excluded (b). NC= No Catch, L= Low, M= Medium, MH= Medium High, H= High.

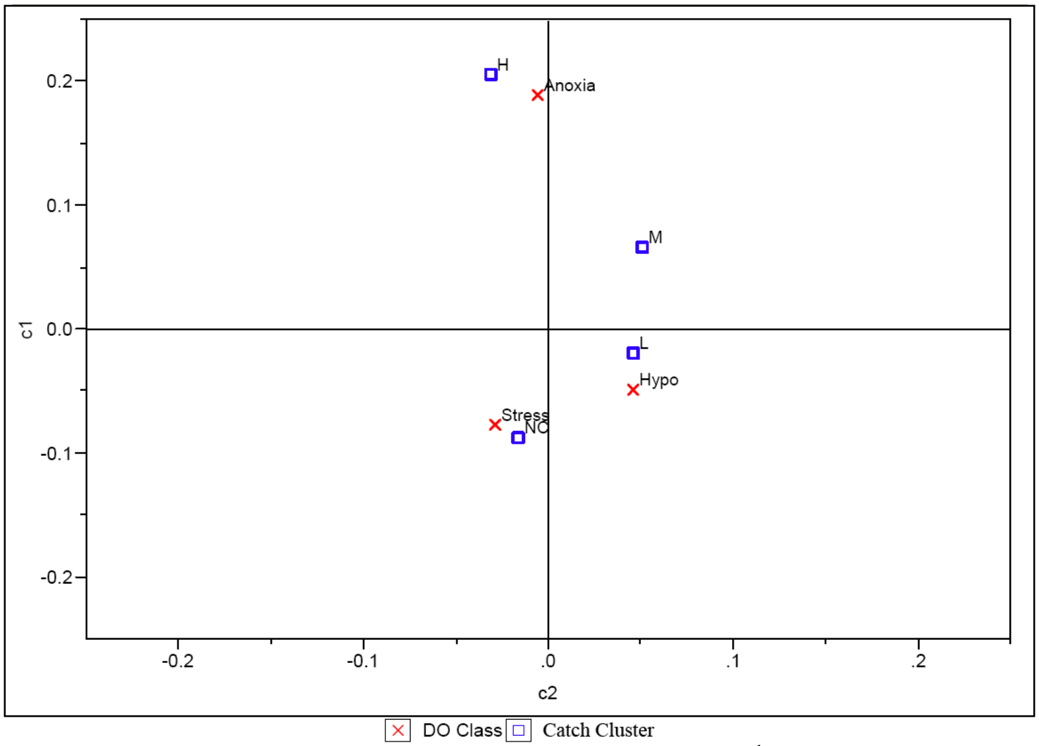


Figure 14. Correspondence analysis for Chesapeake Bay Lower 10th DO Frequency Clusters vs. Catch Clusters with the No Catch class included. NC= No Catch, L= Low, M= Medium, H= High.

The correspondence analysis for DO frequency vs. catch cluster for the lower 25th percentile water quality data with the "No Catch" class included appeared to show that "No Catch" corresponded to hypoxia and DO stress, while low and high catch corresponded to anoxia (Figure 15a). Medium catch and LOK DO levels did not appear to correspond to other groups. Without the "No Catch" class, low catch appeared to correspond to DO stress and hypoxia, medium catch to correspond with LOK DO, and high catch to correspond to anoxia (Figure 15b).

Nominal logistic regression for all DO data in the Chesapeake region for both mean DO (Figure 16a) and DO^2 (Figure 16b) was significant with a Chi square probability of <0.0001 for both, and R-square values of 0.0043 and 0.0034, respectively. Nominal logistic regression was also significant for the lower 10th

percentile DO data with a Chi square probability of 0.0022 and an R-square value of 0.0042 (Figure 17).

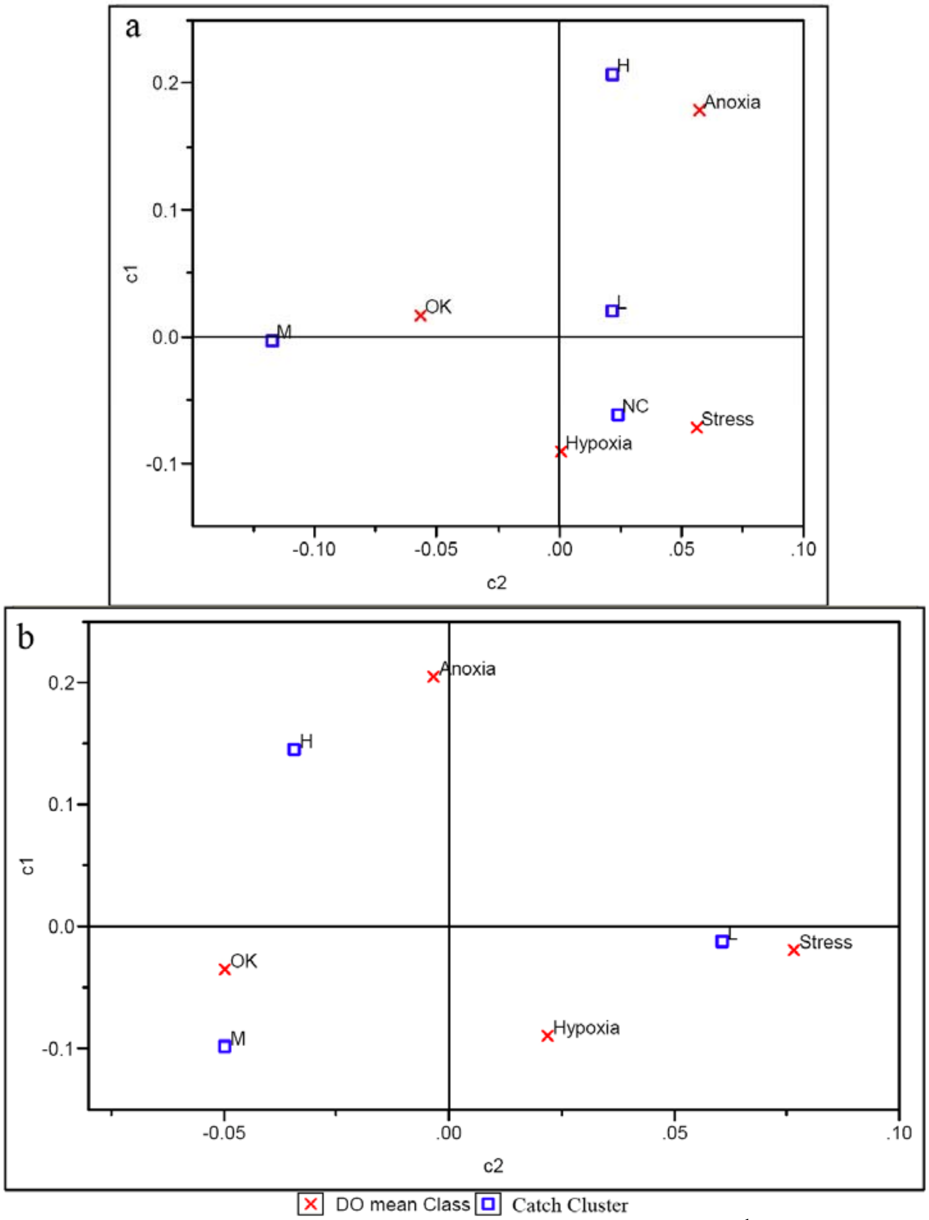


Figure 15. Correspondence analysis for the Chesapeake Bay Lower 25th DO Frequency Clusters vs. Catch Clusters with the No Catch class (NC) included (a) and excluded (b). NC= No Catch, L= Low, M= Medium, H= High.

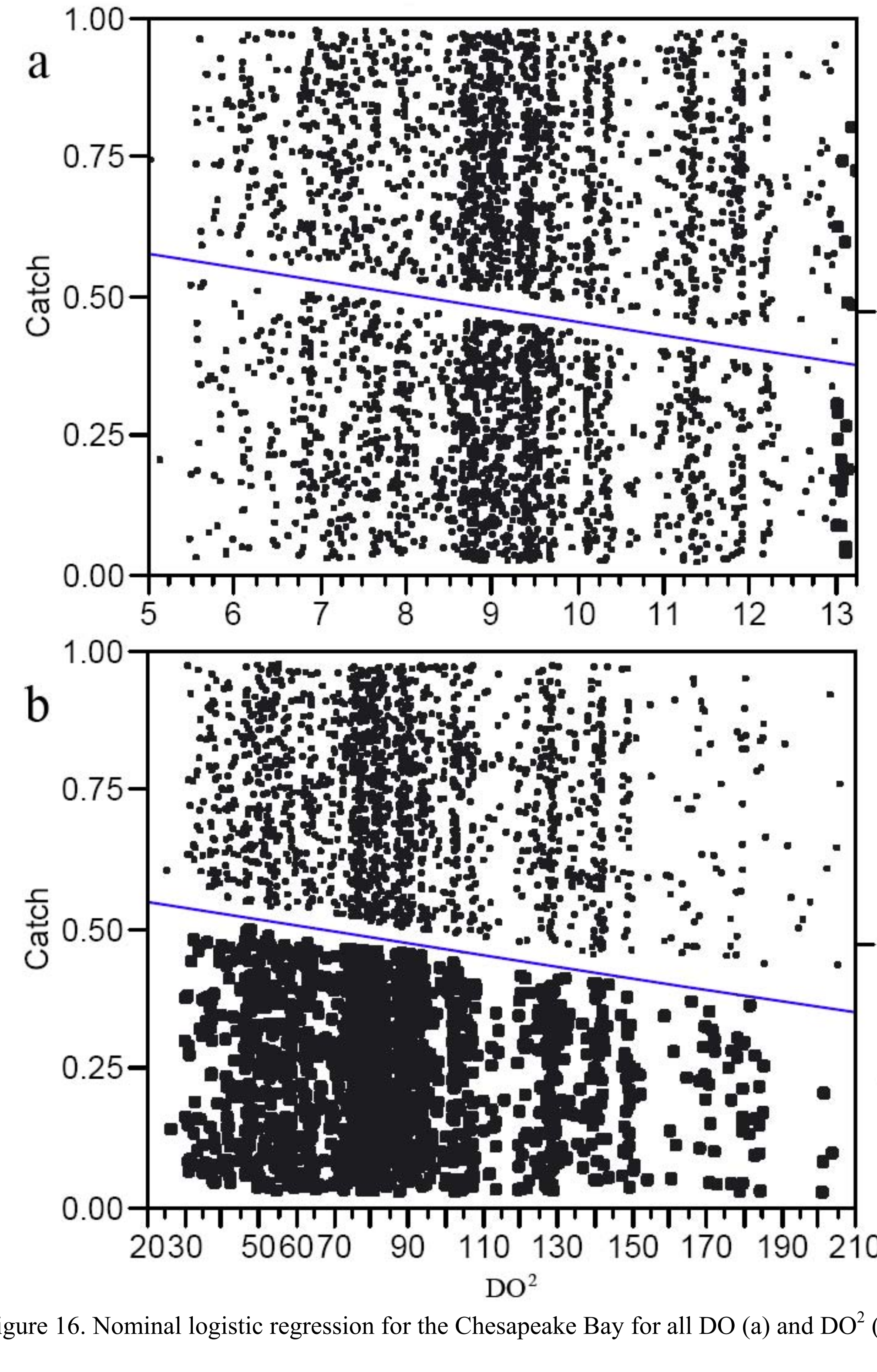


Figure 16. Nominal logistic regression for the Chesapeake Bay for all DO (a) and DO^2 (b).

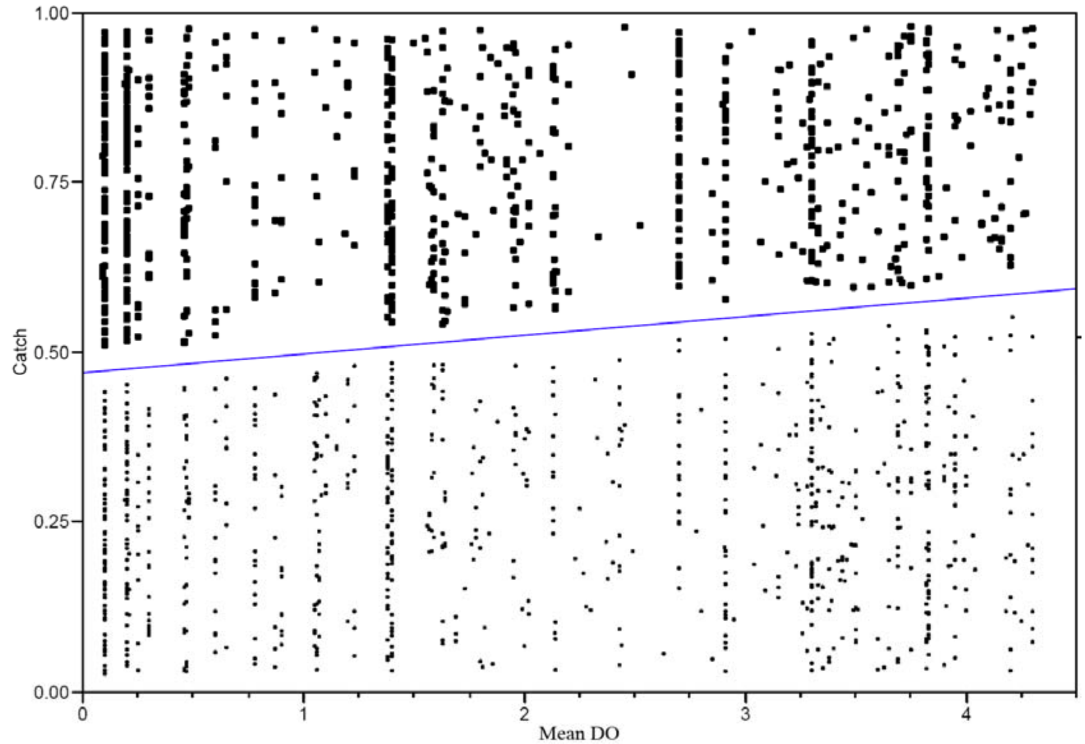


Figure 17. Nominal logistic regression for the Chesapeake Bay Lower 10th DO.

Upper Bay

The only significant results for the Upper Bay region were the cluster analysis on all water quality data for the catch vs. mean DO and DO^2. Both the DO and DO^2 means were significantly different using Tukey's HSD. Based on the ANOVA means the clusters were assigned the names Low (L), Medium Low (ML), Medium High (MH), and High (H) for both DO and DO^2 and Low (L), Medium (M), High (H), and No Catch (NC) for catch. The resulting statistics for DO vs. catch including the "No Catch" class were a Chi squared probability of 0.0360 and an R-squared value of 0.0255. For DO vs. catch excluding the "No Catch" class, the Chi squared probability was 0.0080 with an R-square of 0.0641. Statistics for DO^2 for "No Catch" included and excluded were Chi squared probabilities of 0.0071 and 0.0014, respectively, and R-squared values of 0.0318 and 0.0804, respectively.

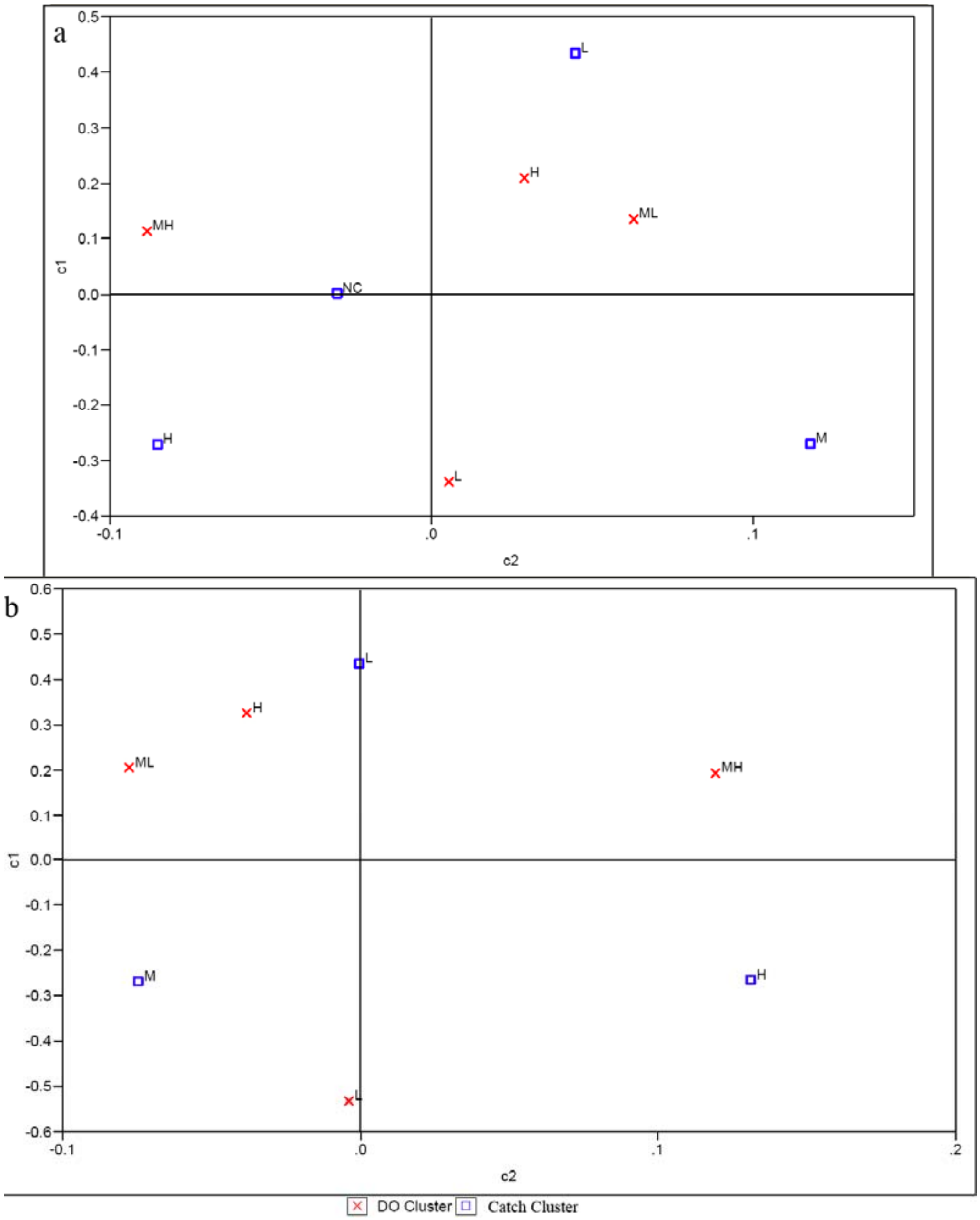


Figure 18. Correspondence analysis for Upper Bay all DO Clusters vs. Catch Clusters with the NO Catch class (NC) included (a) and excluded (b). NC= No Catch, L= Low, ML= Medium Low, M= Medium, MH= Medium High, H= High.

Correspondence analysis for DO vs. catch clusters in the Upper Bay region for all water quality data with the "No Catch" class included appeared to show that "No Catch" corresponded to medium high DO, low catch corresponded to medium low and high DO, and medium catch corresponded to low DO. High catch did not appear to correspond to any DO cluster (Figure 18a). The correspondence analysis without the “No Catch” class appeared to show that low catch corresponded to medium low and high DO while medium catch corresponded with low DO (Figure 18b). High catch and medium high DO did not appear to correspond to other groups.

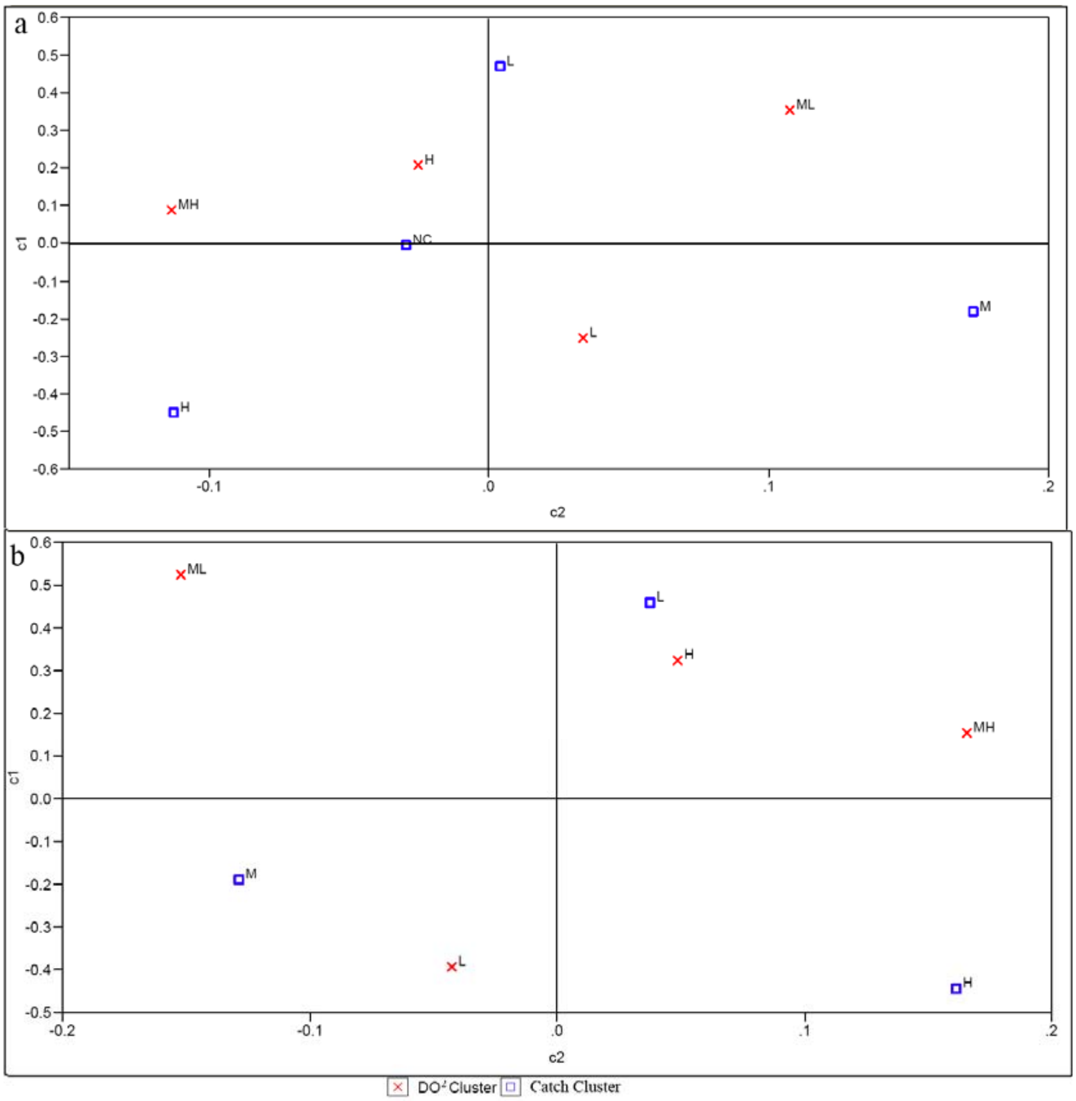


Figure 19. Correspondence analysis for Upper Bay DO^2 Clusters vs. Catch Clusters with the No Catch class (NC) included (a) and excluded (b). NC= No Catch, L= Low, ML= Medium Low, M= Medium, MH= Medium High, H= High.

The correspondence analysis for DO^2 vs. catch clusters with the “No Catch” class included appeared to show that low catch corresponded to medium low DO while medium catch corresponded to low DO (Figure 19a). No catch and high catch did not appear to correspond to any DO clusters while medium high and high DO did not appear to correspond with any catch clusters. With the “No Catch” class excluded correspondence analysis appeared to show that low catch corresponded to medium high and high DO and that medium catch corresponded to low DO (Figure 19b). High catch and medium low DO did not appear to correspond with other clusters.

Middle Bay

Clustering analysis was conducted on all water quality data for the variables mean DO and catch for the Middle Bay region. The means of each of the clusters for all of the Middle Bay for both variables were statistically significant from the others using Tukey’s HSD. Based on the ANOVA means the clusters were assigned the names Low (L), Medium (M), and High (H) for DO, Low (L), Medium Low (ML), Medium High (MH), and High (H) for DO^2, and Low (L), Medium Low (ML), Medium (M), Medium High (MH), High (H), and No Catch (NC) for catch. The Chi squared probability for contingency table analysis for DO vs. catch clusters with the “No Catch” class included was 0.0002 and the R-squared value was 0.0287. The Chi squared probability for contingency table analysis for DO^2 vs. catch with the “No Catch” class was 0.0001 and the R-squared value was 0.0369. For both DO and DO^2, when the “No Catch” class was excluded results were not significant.

Correspondence analysis for DO vs. catch clusters for all water quality data in the Middle Bay region with the “No Catch” class included appeared to show that “No Catch” corresponded to high DO while medium low catch corresponded to low DO (Figure 20). The remaining categories did not appear to correspond to any other opposite cluster. Correspondence analysis for DO^2 vs. catch clusters appeared to show “No Catch” corresponding to medium low and high DO while medium low, medium high, and high catch appeared to correspond to low DO (Figure 21). Neither low catch nor medium high DO appear to correspond to other clusters.

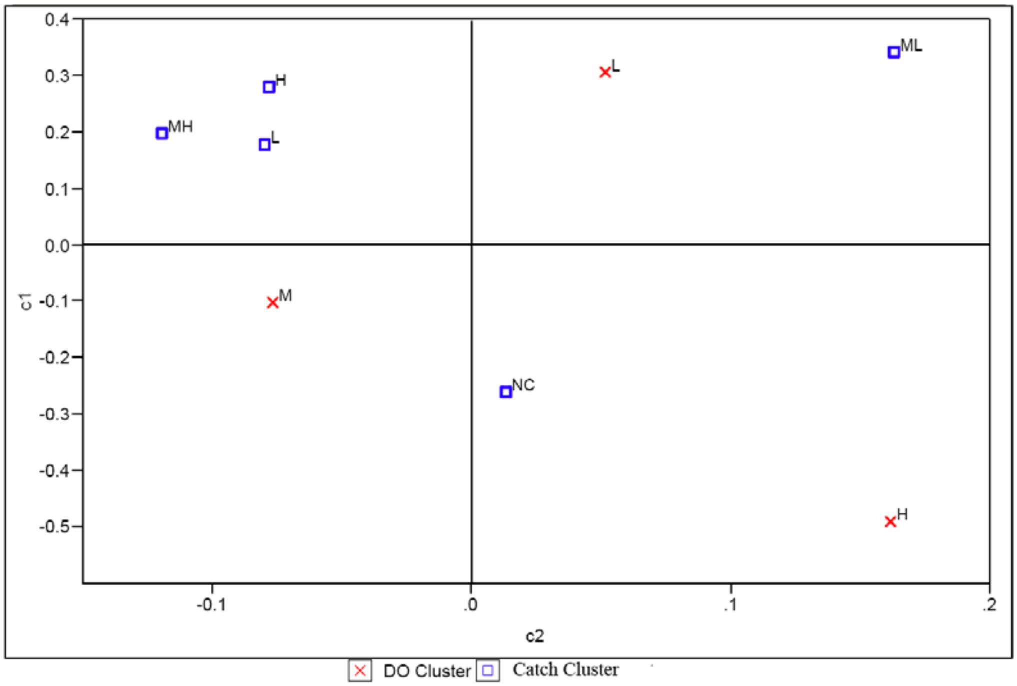


Figure 20. Correspondence analysis for the Middle Bay all DO Clusters vs. Catch Clusters with the No Catch class (NC) included. NC= No Catch, L= Low, ML= Medium Low, M= Medium, MH= Medium High, H= High.

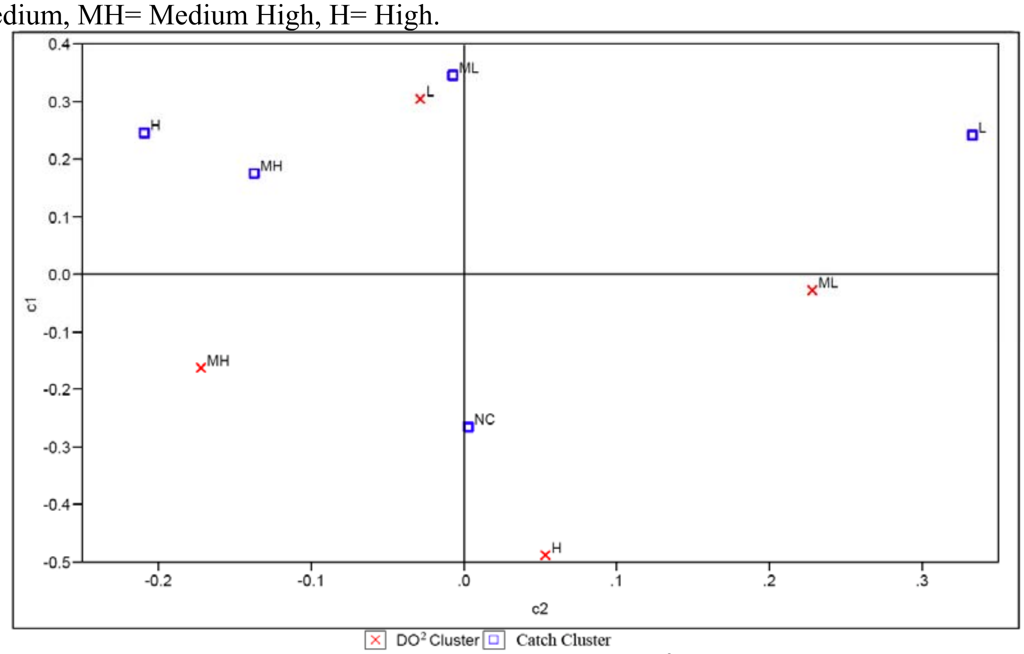


Figure 21. Correspondence analysis for the Middle Bay DO^2 Clusters vs. Catch Clusters with the No Catch class (NC) included. NC= No Catch, L= Low, ML= Medium Low, M= Medium, MH= Medium High, H= High.

The clustering analysis for the same variables as above was also conducted on the lower 10^{th} percentile and lower 25^{th} percentile water quality datasets. The means of all clusters for both the lower 10^{th} and 25^{th} percentiles were all significantly different from each other. Only the mean DO clusters were significant for the contingency and correspondence analysis for the lower 10^{th} percentile. The resulting statistics for the "No Catch" class included and excluded were Chi squared probabilities of 0.0307 and 0.0430, respectively, and R-squared values of 0.0243 and 0.0348, respectively. Like the lower 10^{th} percentile, the lower 25^{th} percentile water quality contingency and correspondence analysis, only the mean DO clusters were significant. The resulting statistics for the "No Catch" class included and excluded were Chi squared probabilities of 0.0278 and 0.0308, respectively, and R-squared values of 0.0259 and 0.0400, respectively.

Correspondence analysis for DO vs. catch clusters for the lower 10^{th} percentile water quality data for the Middle Bay region with the "No Catch" class included appeared to show that low catch corresponded to medium DO, medium catch corresponded to low DO, and high catch corresponded to high DO (Figure 22a). The "No Catch" class did not appear to correspond with any DO clusters. For the "No Catch" class excluded the correspondence analysis appeared to show that low catch corresponded with low DO and high catch corresponded with high DO (Figure 22b). Medium catch and medium DO appear to group, despite being on opposite sides of the c_1-axis.

The correspondence analysis for DO vs. catch clusters for the lower 25^{th} percentile water quality data in the Middle Bay region with the "No Catch" class

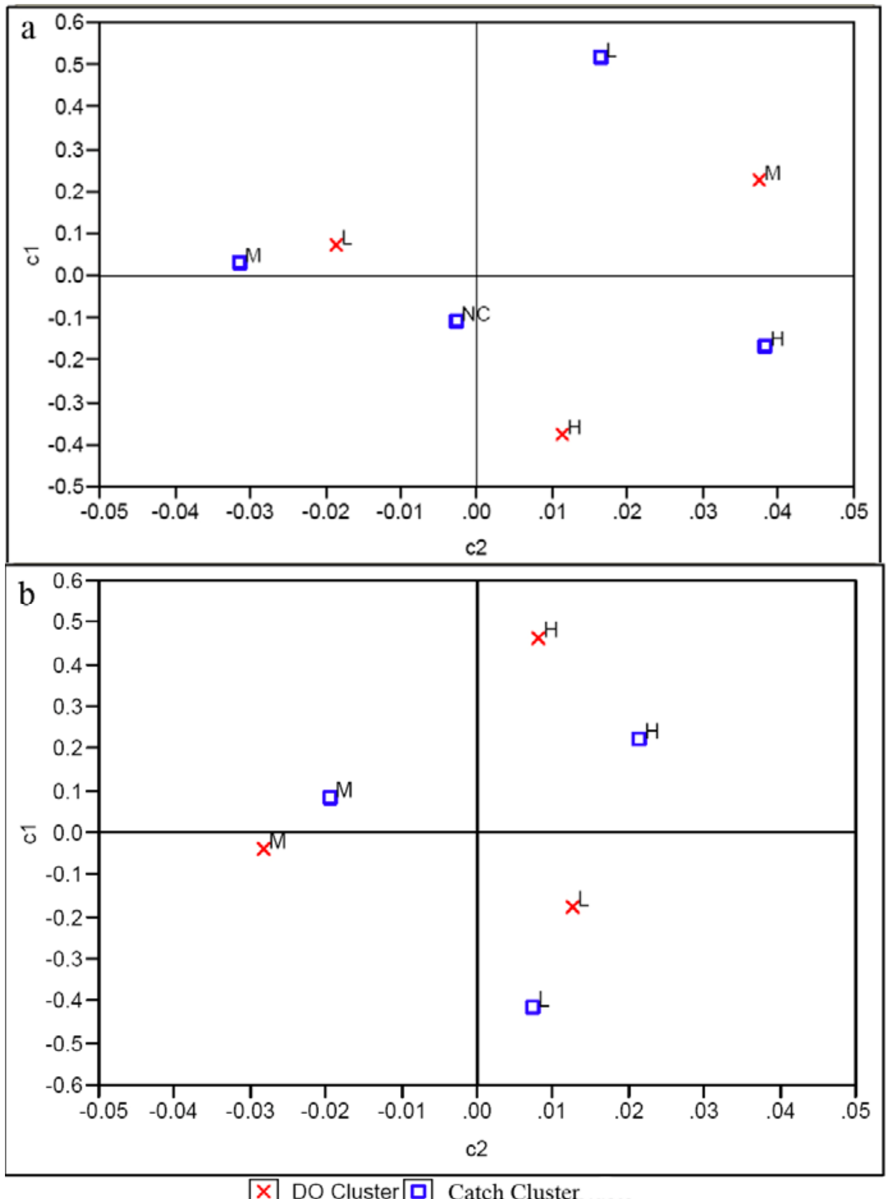


Figure 22. Correspondence analysis for Middle Bay Lower 10th DO Clusters vs. Catch Clusters with the No Catch class (NC) included (a) and excluded (b). NC= No Catch, L= M= Medium, H= High.

included appeared to show that "No Catch" corresponded to high DO, low catch corresponded to medium low, medium catch corresponded to low DO, and high catch corresponded to medium high DO (Figure 23a). The correspondence analysis with the "No Catch" class excluded appeared to show that low catch corresponded to medium low DO, medium catch corresponded to medium high catch, and high catch corresponded with high DO (Figure 23b). Low DO did not appear to correspond with any catch cluster.

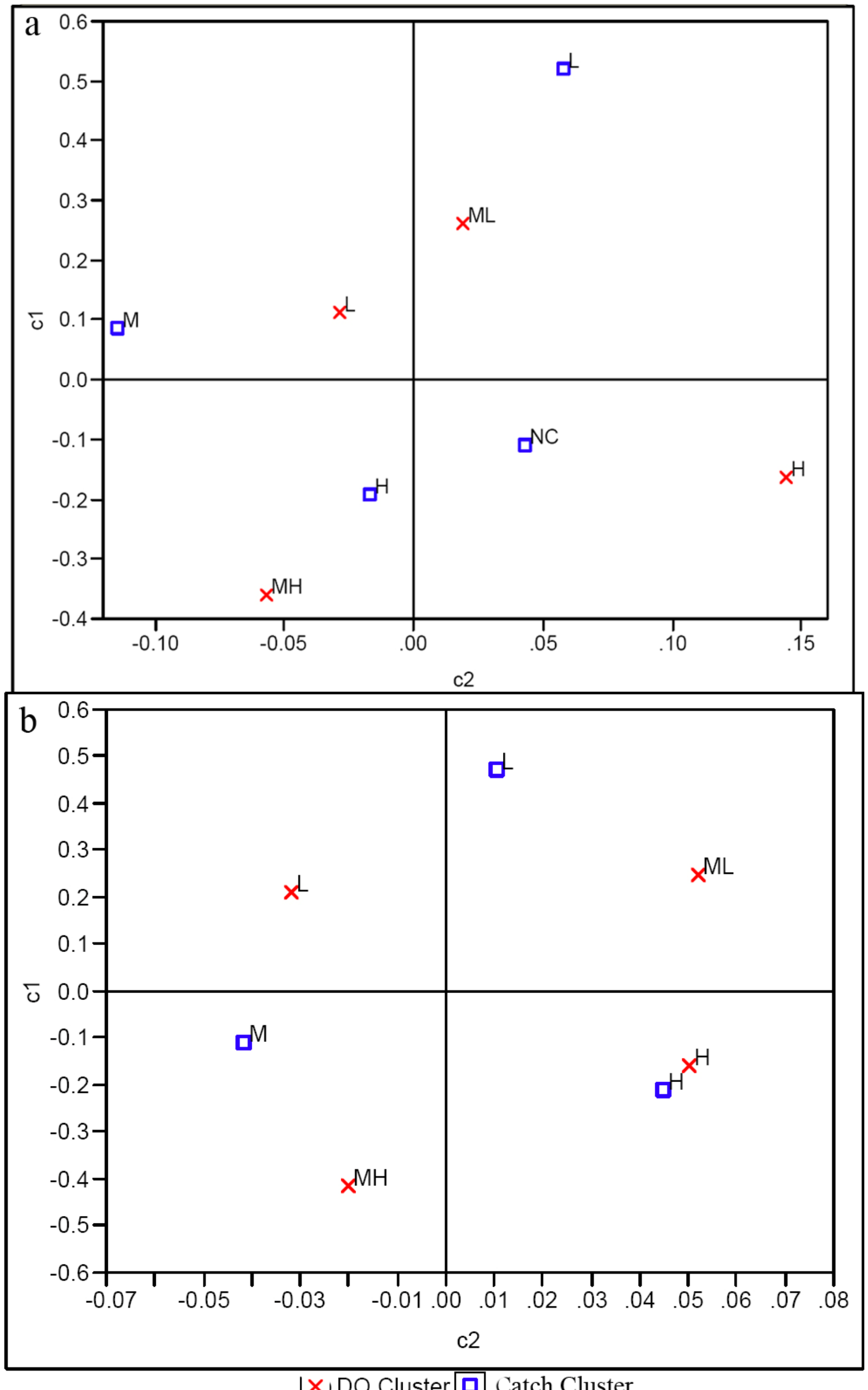


Figure 23. Correspondence analysis for Middle Bay Lower 25th DO Clusters vs. Catch Clusters with the No Catch class (NC) included (a) and excluded (b). NC= No Catch, L= ML= Medium Low, M= Medium, MH= Medium High, H= High.

DO frequency vs. catch cluster contingency and correspondence analysis for the entire Middle Bay region was only significant for the 10th and 25th percentile water quality datasets. For the 10th percentile the resulting statistics for the "No Catch" class included were a Chi squared probability of 0.0247, and an R-squared value of 0.0240. Results for the "No Catch" class excluded were a Chi squared probability of 0.0283, and an R-squared value of 0.0385. The statistics for the lower 25th percentile for the "No Catch" class included was a Chi squared probability of 0.0143 and an R-squared value of 0.0247. Results for the "No Catch" class excluded were not significant.

Correspondence analysis for DO frequency vs. catch cluster for the lower 10th percentile water quality data with the "No Catch" class included appeared to show that low catch corresponded to anoxia, medium catch corresponded with hypoxia, and high catch corresponded to DO stress (Figure 24a). The "No Catch" did not appear to correspond with any DO frequency class. With the "No Catch" class excluded, low catch corresponded to anoxia and high catch appear to correspond to DO stress (Figure 24b). Neither medium catch nor hypoxia appeared to corresponded with another group.

The correspondence analysis for DO frequency vs. catch cluster for the lower 25th percentile water quality data with the "No Catch" class included appeared to show that low catch corresponded to hypoxia, and high catch corresponded to DO stress (Figure 25). Anoxia, "No Catch", and medium catch did not appear to directly correspond to any opposite class.

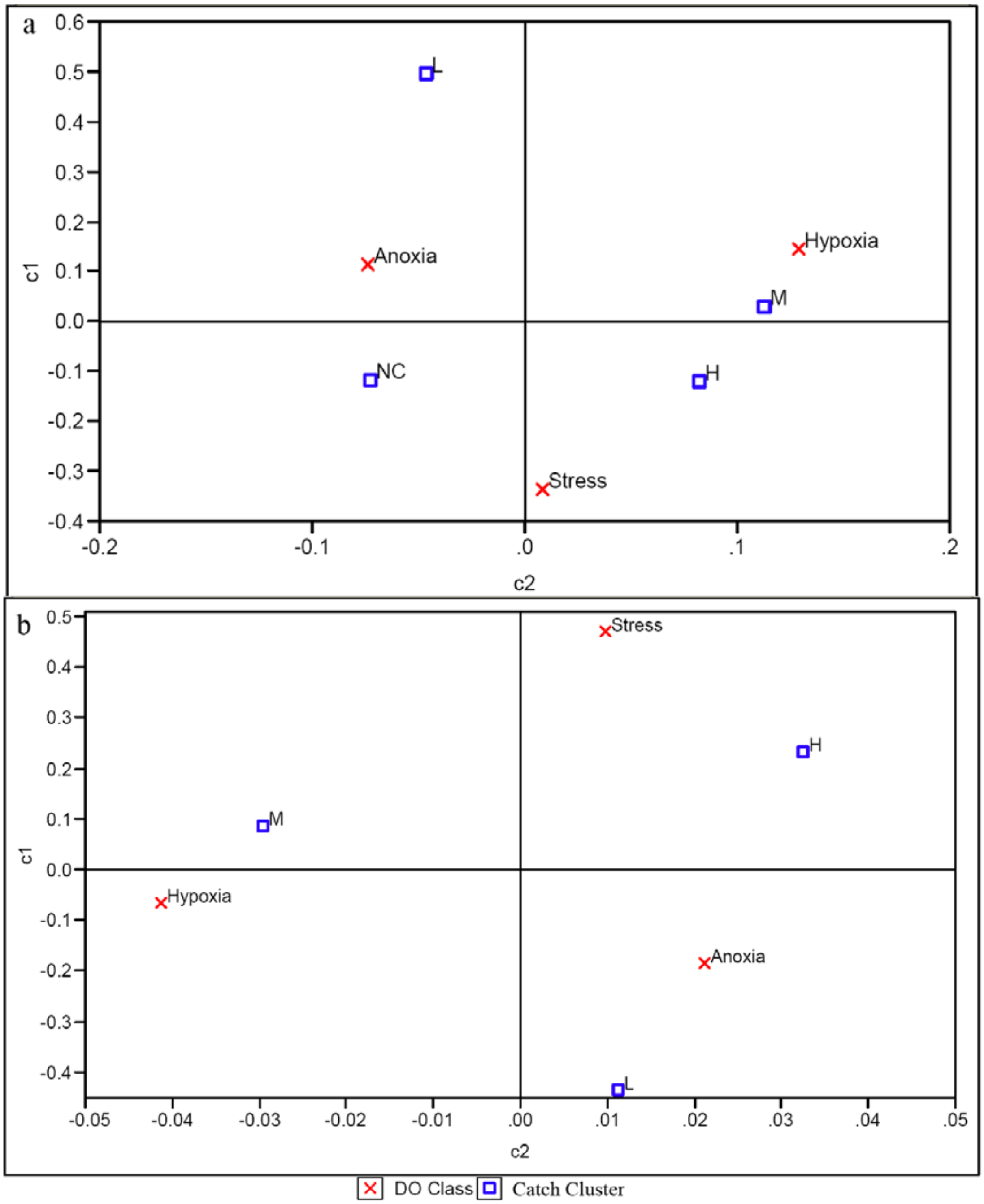


Figure 24. Correspondence analysis for Middle Bay Lower 10th DO Frequency vs. Catch Clusters with the No Catch class (NC) included (a) and excluded (b). NC= No Catch, L= Low, M= Medium, H= High.

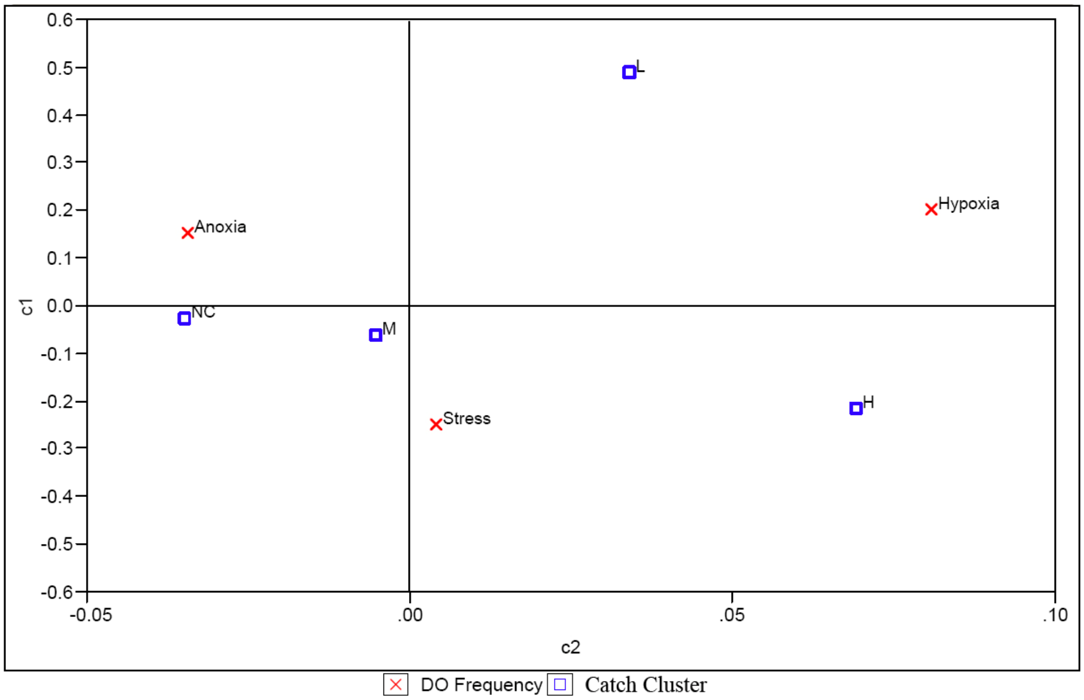


Figure 25. Correspondence analysis for Middle Bay Lower 25th DO Frequency vs. Catch Clusters with the No Catch class (NC) included. NC= No Catch, L= Low, M= Medium, H= High.

Nominal logistic regression for all DO data in the Middle Bay region for both mean DO (Figure 26a) and DO^2 (Figure 26b) was significant with a Chi square probability of <0.0001 for both, and R-square values of 0.0318 and 0.0432, respectively. Nominal logistic regression was also significant for the lower 25th percentile DO (Figure 26c) data with a Chi square probability for the whole model of 0.0188 and an R-square value of 0.0114. The positive mean DO parameter estimate was 0.1410 and significant with a Chi square probability of 0.0197.

Lower Bay

Clustering analysis was conducted on all water quality data for the variables mean DO and catch for the Lower Bay region. The means of each of the clusters for all of the Lower Bay for both variables were statistically significant from the others using Tukey's HSD. Based on the ANOVA means the clusters were assigned the

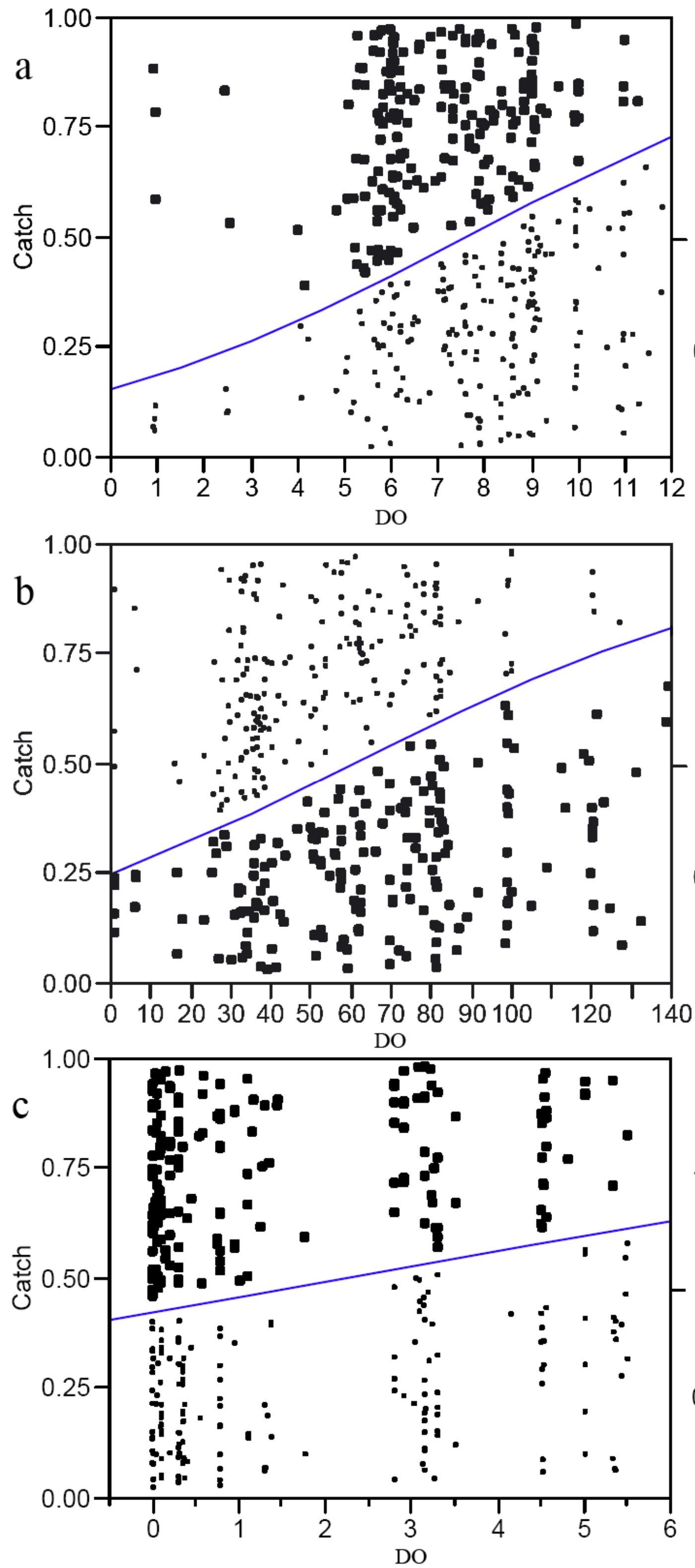


Figure 26. Nominal logistic regression for the Middle Bay for all DO (a), DO^2 (b), and Lower 25^{th} DO (c).

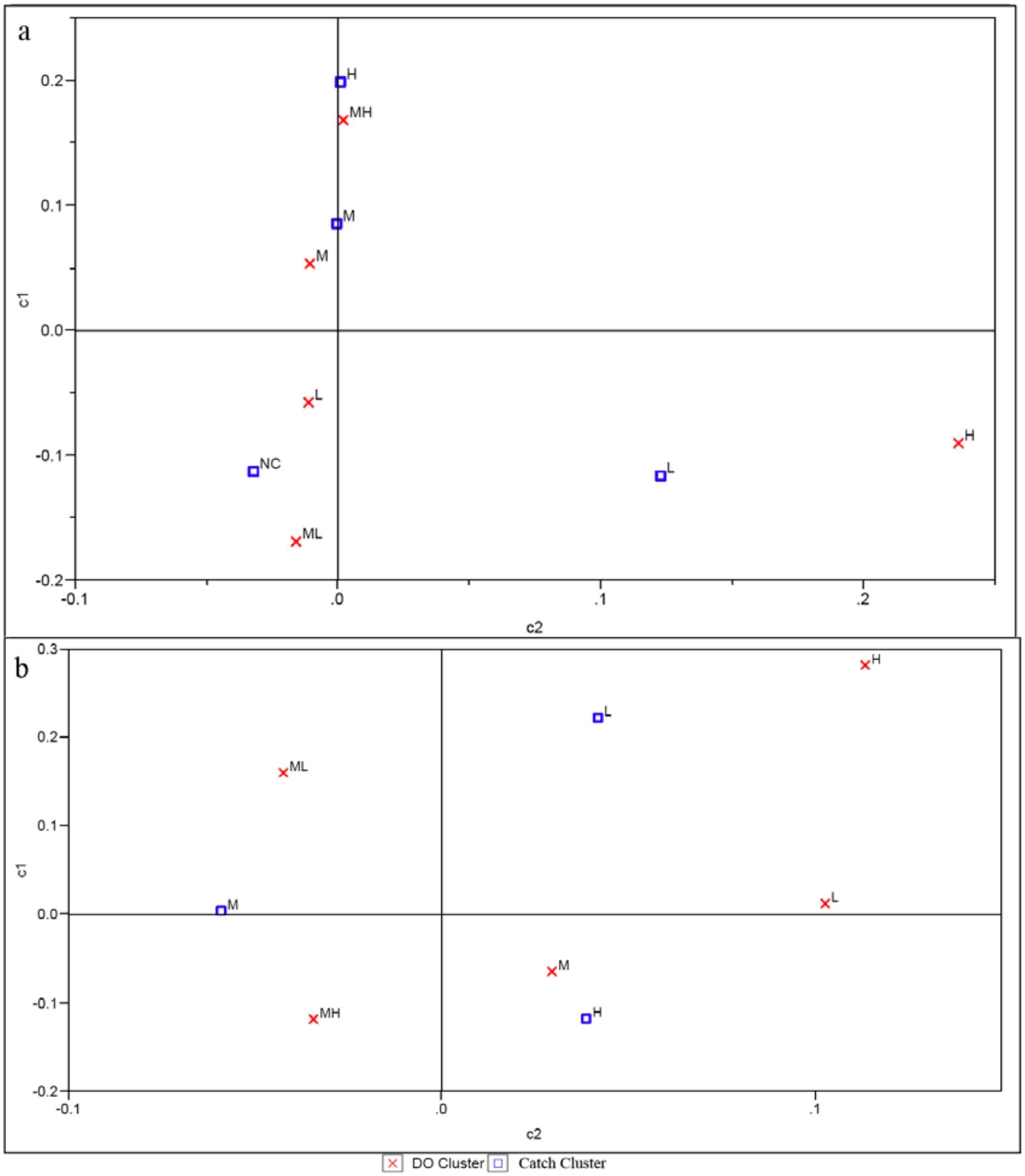


Figure 27. Correspondence analysis for Lower Bay all DO Clusters vs. Catch Clusters with the No Catch class (NC) included (a) and excluded (b). NC= No Catch, L= Low, ML= Medium Low, M= Medium, MH= Medium High, H= High.

names Low (L), Medium Low (ML), Medium High (MH), and High (H) for both DO and DO^2, and Low (L), Medium (M), High (H), and No Catch (NC) for catch. The Chi square probabilities for contingency table analysis for DO vs. catch clusters with the "No Catch" class included and excluded was 0.0001 and 0.0190, respectively and the R-squared values were 0.0082 and 0.0084, respectively. The Chi squared probability for contingency table analysis for DO^2 vs. catch with the “No Catch” class included and excluded was <0.0001 and 0.0157, respectively and the R-square values were both 0.0087.

Correspondence analysis for DO vs. catch clusters for all water quality data in the Lower Bay region with the “No Catch” class included appeared to show that “No Catch” corresponded with low and medium low DO, low catch corresponded with high DO, medium catch corresponded with medium DO, and high catch corresponded with medium high DO (Figure 27a). With the “No Catch” class excluded, low catch appear to correspond to both low and high DO, medium catch appeared to correspond to medium low DO, and high catch appeared to correspond with medium DO (Figure 27b). Medium high DO did not appear to correspond with any catch class.

The correspondence analysis of DO^2 clusters vs. catch clusters for all water quality in the Lower Bay region with the “No Catch” class included appeared to show that “No Catch” corresponded to medium low DO, low catch corresponded to both low and high DO, and medium catch corresponded to both medium and medium high DO (Figure 28a). High catch did not appear to correspond with any DO cluster. With the “No Catch” class excluded low catch appeared to correspond with both low and high DO, medium catch appeared to correspond with medium low DO, and high catch appeared to correspond with medium DO (Figure 28b). Medium high DO did not appear to correspond with any catch cluster.

Nominal logistic regression for all DO data in the Lower Bay region for both mean DO (Figure 29a) and DO^2 (Figure 29b) was significant with a Chi square probability of <0.0001 for both, and R-square values of 0.0318 and 0.0432, respectively.

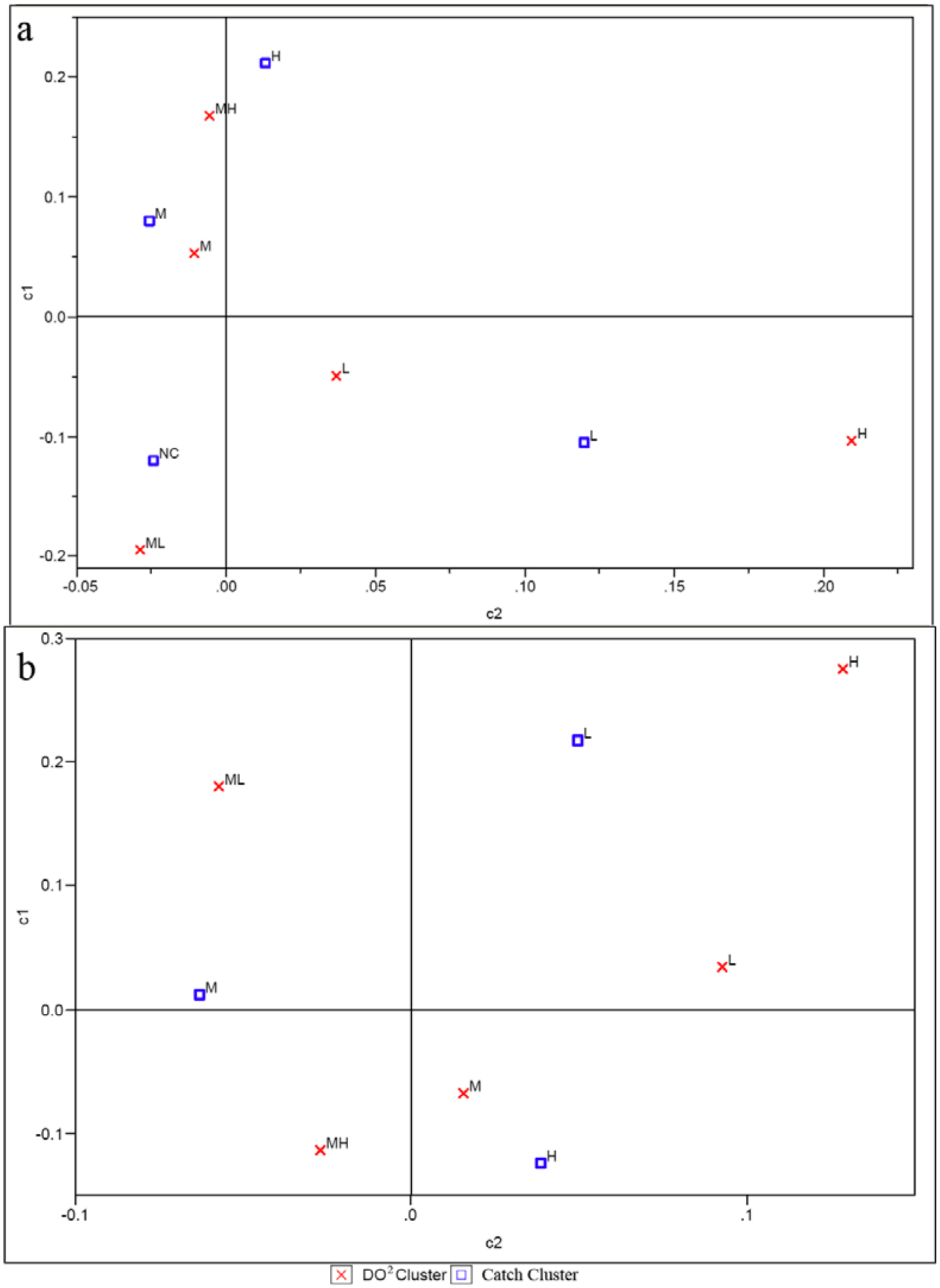
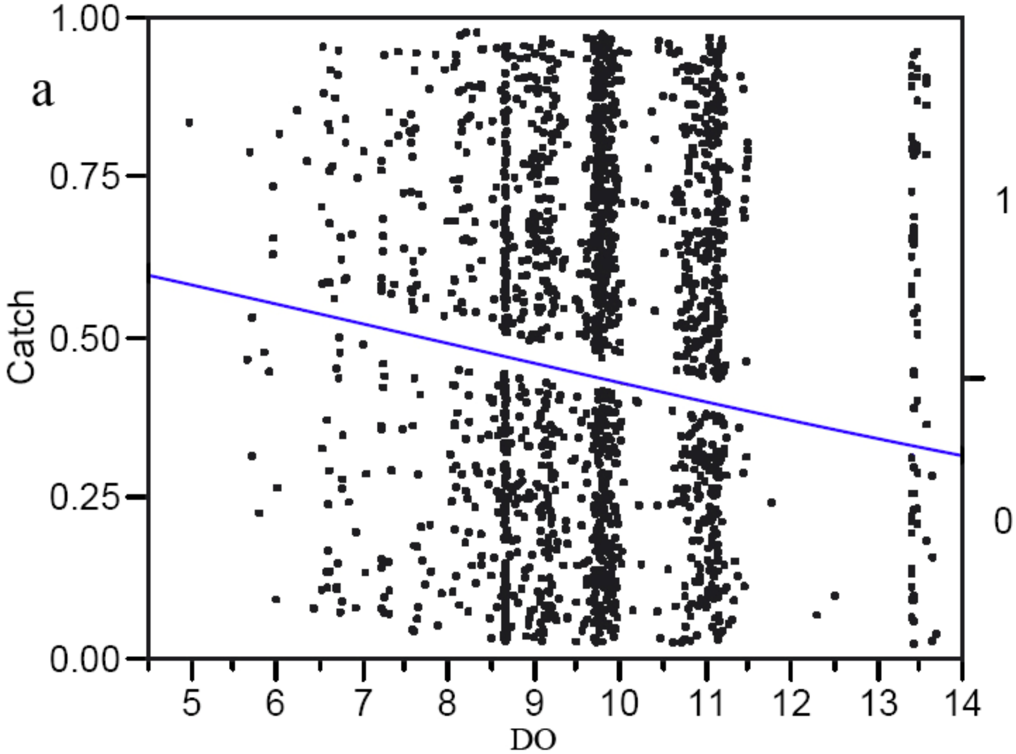


Figure 28. Correspondence analysis for Lower Bay DO^2 Clusters vs. Catch Clusters with the No Catch class (NC) included (a) and excluded (b). NC= No Catch, L= Low, ML= Medium Low, M= Medium, MH= Medium High, H= High.



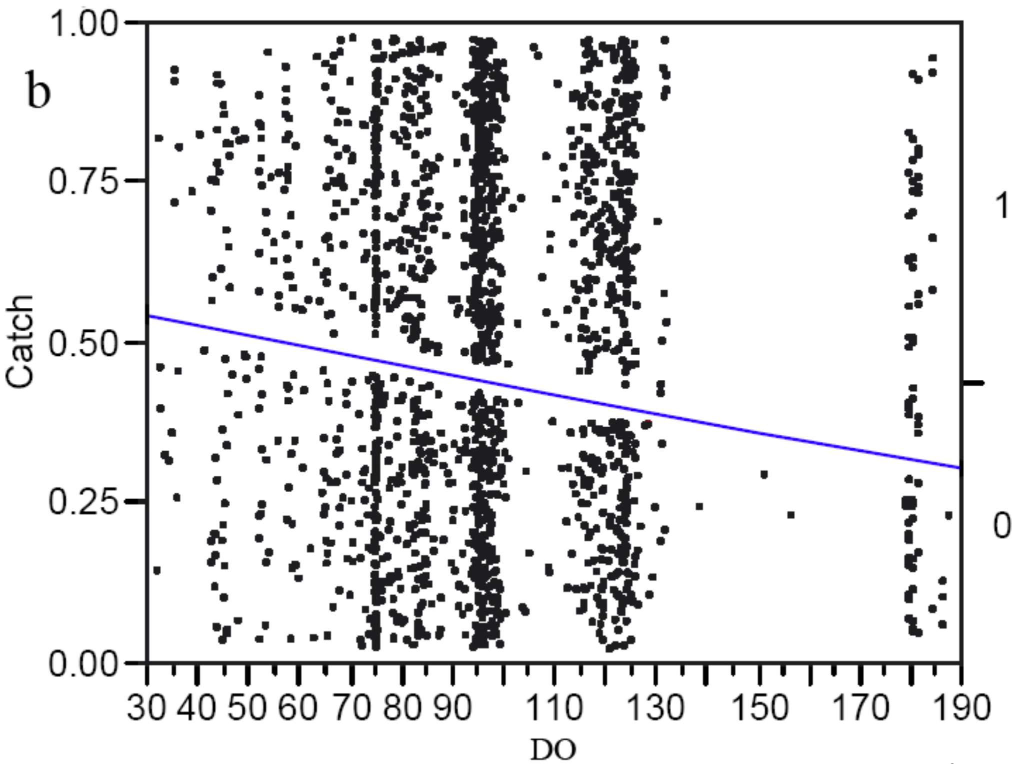


Figure 29. Nominal logistic regression for the Lower Bay for all DO (a) and DO^2 (b).

Patuxent River

There were no statistically significant results at all in the Patuxent River region.

Potomac River

There were no statistically significant results at all in the Potomac River region.

Discussion

Model Results

The parameter estimate results for the point water quality data versus the interpolated water quality results appear to show the point data inflating the parameter estimate. However, using equations 2 and 3 it was found that none of the parameter estimates for any sub-region were significantly different between point water quality data and interpolated water quality data.

For the Chesapeake Bay as a whole, and for the Upper and Middle Bay sub-regions, DO significantly influenced the recreational striped bass catch. In each of these cases DO was the largest contributing variable to striped bass catch, followed by the mean striped bass catch and hours fished. All other variables in general were orders of magnitude smaller. Following Bricker et al. (2006), where the models were reasonable (significant results) they were used to predict striped bass catch at key DO concentrations. The expected striped bass catch for the Chesapeake Bay as a whole over the 2000-2006 time-period at mean DO concentrations of 9.28 mg/L was 5.85 striped bass per fisherman per trip. When the DO concentration is set at 5 mg/L or the upper level of biological stress, the corresponding expected striped bass catch is 2.03 (Table 7). When the DO concentration is set at 2 mg/L or the upper level of hypoxia, the corresponding expected fish catch drops to 0.67 striped bass per angler per trip. The change in expected striped bass catch between 2 mg/L to 5 mg/L DO represents an increase of 149.4%.

For the Upper Bay sub-region, the expected striped bass catch for the 2000-2006 time-period at mean DO concentrations of 8.35 mg/L was 9.90 striped bass per fisherman per trip. When the DO concentration is set at 5 mg/L the model predicts a drop to 3.98 striped bass per fisherman per trip (Table 7). When the DO concentration is dropped to 2 mg/L the corresponding expected striped bass catch decreases to 0. The change in expected striped bass catch between 2 mg/L to 5 mg/l DO represents and infinite increase since at 2 mg/L the expected catch is 0.

System/Region	Expected Fish Catch at Mean DO Conditions	Expected Fish Catch at 5 mg/L	Expected Fish Catch at 2 mg/L DO	Percent Increase from 2 to 5 mg/L
Chesapeake Bay*	(mean = 9.28 mg/L) **5.85**	2.03	0.67	149.4
Upper Bay*	(mean = 8.35 mg/L) **9.90**	3.98	0	Undefined
Middle Bay*	(mean = 7.49 mg/L) **0.25**	0	0	0
Long Island Sound**	(mean = 7.18 mg/L) **2.75**	2.77	2.71	2.1
Patuxent River**	(mean = 5.99 mg/L) **7.63**	6.27	2.16	65.5
Potomac River**	(mean = 4.53 mg/L) **4.07**	4.55	1.45	68.1

Table 7. Striped bass expected fish catch (per angler per trip) results at mean and predictive conditions. *= Results from this study (2000-2006), **= Results from Bricker (2006) (August 2002 data).

For the Middle Bay sub-region, the expected striped bass catch for the 2000-2006 time-period at mean DO concentrations of 7.49 mg/L was 0.25 striped bass per fisherman per trip. When the DO concentration is set at 5 mg/L the corresponding striped bass catch is 0 striped bass catch per fisherman per trip (Table 7). The same is true when the DO concentration is set to 2 mg/L DO. Since the modeled striped bass catch for 5 mg/L and 2 mg/L DO are both 0, the percent change between the two is 0 as well.

The difference in the expected striped bass catch between the two sub-regions and the Bay as a whole shows the variability caused by changes in habitat, depth, and susceptibility to low DO concentrations. Figure 30 shows average summer DO concentrations, using the same interpolated DO data as that in this study, in the Chesapeake Bay with the sub-region boundaries marked. As Figure 30 shows, the Middle Bay is most susceptible to low DO concentrations and as the model predicts, has the lowest expected striped bass catch of the sub-regions where the model was significant.

As can be seen in the model predictions, the striped bass are migrating out of the areas of low DO concentrations and are being caught in larger numbers in regions where the DO concentrations are higher. This relationship is also solidified by the non-parametric statistical analysis which the next section covers in detail.

The generally low R-square values for most results in this study (Tables 3 and 4) are to be expected as in a region as large and dynamic as the Chesapeake Bay, the number of variables that contribute to the probability and ability of a fisherman to catch striped bass are numerous. When only looking at a few variables' effect on the estimated total striped bass catch the amount of variability that these variables account for, while significant, should be low.

Non-parametric Results

The majority (55%) of DO cluster and frequency analysis when significant followed expected relationships of low catch corresponding to low DO and high catch corresponding to high DO (Table 8). Of the remaining analysis only 10% showed clear relationships between the two categories. However, these relationships were exactly inverse to what the expected outcome would predict. The cause of this phenomenon is unclear, however it only occurred during the DO frequency analysis. Two additional analysis, cluster analysis for all DO in the Middle and Lower regions, followed the expected outcome with the exception of the high DO cluster corresponding to no catch (NC) (Table 8). It is important to note that in both these cases that the high DO class includes only DO 12 mg/L and above. Temporal variability may possibly play a role in the explanation of this result, such that DO concentrations in the Bay tend to be highest in the winter months (November through February) during the off season for striped bass in the Chesapeake Bay.

The statistically significant results of the tests favored the Chesapeake Bay as a whole, and the Middle Bay region. The lack of statistical significance in the Patuxent and Potomac rivers for both types of cluster analysis (cluster analysis for total catch and DO and cluster and frequency analysis for total catch and DO, respectively) can possibly be attributed to lack of data. The lack of statistical significance for the Upper and Lower Bay regions, with the exception of cluster analysis for all water quality data for both regions and nominal logistic regression for all water quality data for the Lower Bay, is likely due to a number of different factors. For the Lower Bay it is speculated that many of the fisherman may actually have been

		No Catch Included		No Catch Excluded	
		Cluster Analysis	Frequency Analysis	Cluster Analysis	Frequency Analysis
Chesapeake Bay	All	EX		EX	
	25th	UC	UC	UC	IR
	10th	EX	IR	UC	
Upper Bay	All	UC		UC	
	25th				
	10th				
Middle Bay	All	EX*			
	25th	UC	EX	EX	
	10th	EX	EX	EX	EX
Lower Bay	All	EX*			
	25th				
	10th				

EX = Generally expected outcome. Represents approximately 55% of significant results.
UC = Unclear results. Represents approximately 35% of significant results.
IR = Inverse expected relationship shown in both extreme categories. Represents approximately 10%.
*Denotes where expected results deviated only in that the high DO (>12 mg/L) corresponded to no catch (NC).

Table 8. Summary of non-parametric DO cluster and frequency analysis with the No Catch class included and excluded.

leaving the Bay and fishing in nearshore and coastal waters instead of actually inside of the Bay. This would serve to mask the relationship between DO and striped bass catch in that the estimated water quality for where the fisherman fished would be inaccurate. Other factors that may play a role in the Lower Bay may be the overall depth and size of the region as well as the increased tidal flushing as compared to other regions of the Bay. Striped bass are sensitive to changes in DO concentrations (Breitburg et al. 1997), and are likely to leave areas of low DO (and possibly areas of very high DO as described later). However, in deeper waters where stratification is present, or in larger more open geographical areas the striped bass may be able to migrate higher up into the water column or move to a different location still within the region (e.g. the Lower Bay) and be caught there despite low DO concentrations in bottom waters (Bricker et al. 2006) (see Figure 30). Also, when looked at over larger regions, (e.g. the whole Chesapeake and the Lower Bay) when extreme low DO events decrease the available habitat for Striped bass, it is speculated that the fish may essentially be corralled into a smaller area making the density of fish per area of water greater, thereby increasing the chances of catching a fish. Modern fishermen are easily equipped with fish locating devices which would also serve to help them in locating areas of greater fish density.

It is important to note that many organisms change their behavior including feeding habits when under stressful conditions caused by chemical changes to their environment (Van der Oostet al. 2003). Breitburg et al. (1997) found that predation by juvenile Striped bass decreased in low but non-lethal DO events. This would help to explain why catch is expected to decrease as DO levels drop.

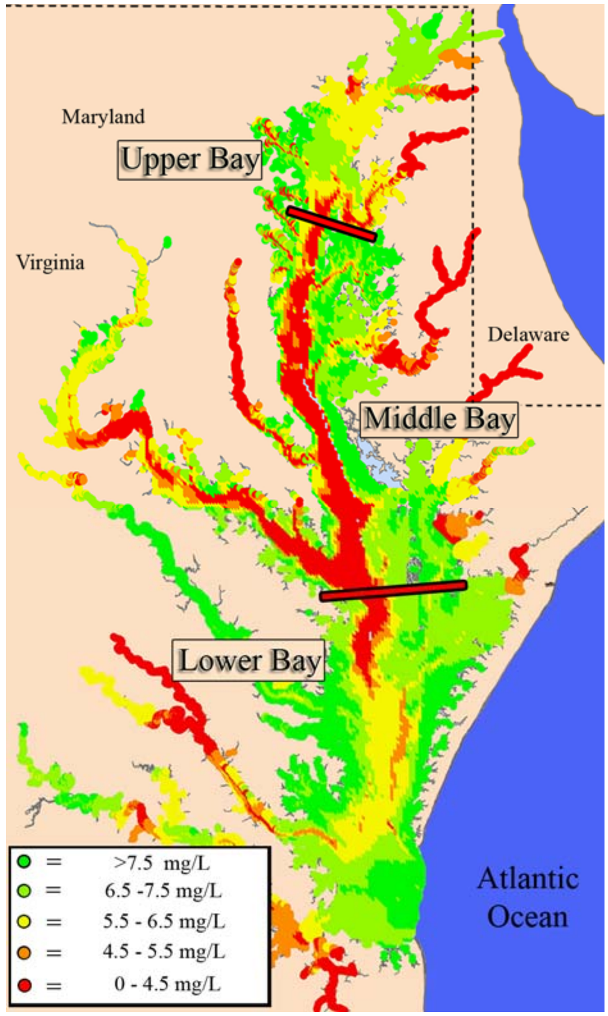


Figure 30. Map of dissolved oxygen concentrations for July 2006 in the Chesapeake Bay.

Figure 5 gives a generalized view of the locations of the water quality used to calculate the statistics for each region and data subset (i.e. the lower 10^{th} and 25^{th} percentiles). It is not surprising that the regions with the most even distribution of water quality had greater numbers of statistically significant results as well as results closer to the expected result of increased striped bass catch with increasing DO.

For the entire Chesapeake Bay, results for the clustering analysis for all water quality mean DO vs. catch clustering were close to the expected outcome of increasing fish catch with increasing DO (Figure 10). The results for mean DO^2 were even closer to the expected result with “No Catch” appearing to being associated with low DO where the “No Catch” was included and high catch associated with high DO without the “No Catch” class (e.g. the effect of DO only when fish were actually caught) (Figure 11). For the lower 10th percentile the data distribution of the DO covers 0.09 mg/L to 4.3 mg/L and covers most of the entire range of DO of interest. The lower 25th percentile covers the entire range of DO of interest from 0.09 mg/L to 5.95 mg/L. The clustering correspondence also appears to tend to follow the results of Breitburg et al. (1997) in that for the high DO cluster medium catch was shown, and for the medium high DO cluster, low catch was shown (e.g. decreasing catch or striped bass feeding activity as DO decreased). However, the lower 10th and 25th percentile clusters for DO vs. catch appear to show an inverse relationship to the expected outcome (Figures 13 and 14). This type of relationship was seen repeatedly throughout the analysis for Chesapeake Bay 10th and 25th percentile (both for DO clusters and for DO frequency - Figures 13-16). It is speculated that there are multiple spatial-temporal variations in both fish behavior (e.g. migration, feeding, growth, and/or reproductive habits) and DO variability (e.g. seasonal variation) that may account for this relationship. For example, an exact date or season that the fishing effort occurred in is not intentionally chosen or selected, rather initially the entire year of data (averaged down to a single monthly value for all water quality variables) is made available for the analysis. However, by taking the lower 25th and 10th subsets, a natural tendency towards the summer months is introduced. When looking at the entire Chesapeake, seasonal variability may also play a role in this inverse expected relationship. Since in the Chesapeake, the highest DO levels may be experienced during the winter months when striped bass are naturally less likely to be caught, thus possibly causing this apparent relationship between very high DO and low or no catch. Another possible explanation comes from Dauer et al. (1992). They found that extreme low DO (<2 mg/L) in the Chesapeake Bay caused lower diversity and biomass in the macrobenthic communities which support juvenile striped bass. This lower availability can cause higher competition for food and may in part account for the increased striped bass catch during extremely low DO. As the fish are forced higher in the water column in the search for food that is less available, they may find fishing bait more 'attractive'.

As previously mentioned in the DO vs. catch analysis DO frequency class vs. catch for the lower 10^{th} and 25^{th} water quality datasets for the entire Chesapeake tended to show inverse relationships. These inverse relationships are basically identical to those above because they represent the same dataset and the DO frequency classes are essentially proxies for the DO clusters.

When the Bay was divided up into the sub-regions an interesting relationship appeared in the DO vs. catch clustering for all water quality. The correspondence analysis plots generally follow the expected outcome of increasing catch with increasing DO with the distinct exception that for each sub-region, the highest DO cluster most often corresponded to the low or "No Catch" clusters (Figures 19-26, 28-29). Further studying of the data appears to show that for all water quality the highest DO cluster generally included only DO values 12 mg/L and above. It also appears that not only does the positive effect of increasing DO on catch taper off at higher levels, it actually looks as though at very high levels of DO reduced striped bass catch is shown. This phenomenon is the same as the inverse relationship described above, and again is speculated to be caused by spatial-temporal variations in both fish behavior and DO variability. Nominal logistic regression analysis for the whole Bay and for the Lower Bay region support this conclusion showing a decreasing probability of catching a fish as DO climbs into the upper OK and very high ranges(>12 mg/L) (Figures 17 and 30). The distribution of DO data for the nominal logistic regression for both the whole Bay and the Lower region generally ranged from 5 mg/L through 13.5 mg/L. These datasets naturally exclude the lower DO that is of interest for the other tests (as do all the datasets that include all water quality).

Results for the Middle Bay lower 10th and 25th percentile data showed very well the expected relationship between increases in striped bass catch as DO increases (Figures 23 and 25). For the Middle Bay both DO subsets always showed high catch clusters correlating with the high DO cluster or the highest DO frequency class (DO Stress). The other clusters and frequencies for DO followed suit corresponding to their catch cluster counterpart (e.g. medium catch with medium DO, or low catch with anoxia).

For the whole Chesapeake Bay, the data showed that when a striped bass was caught, on average the DO was approximately 9 mg/L (Table 7). Hill et al. (1981) found that striped bass preferred water with DO levels above 7.5 mg/L if available. This correlates well with the nominal logistic regression results for the whole Middle Bay region where it was found that the threshold of catching a striped bass versus not catching striped bass occurs at approximately 7.8 mg/L of DO (Figure 26). Looking at the nominal logistic regression for the whole Bay again (Figure 16), the decreasing relationship crosses the catch versus no catch threshold at approximately 9 mg/L DO.

These combined results point toward a possible optimum DO range for catching striped bass in the Chesapeake Bay hinging around 8-9 mg/L DO.

The reason for the differences in available rows of data (as seen in Table 7) between the three subsets of water quality data is caused by the loss of fisherman interview records due to lack of water quality variables for those records. The lack of water quality variables stems from the partitioning of the total water quality dataset into the subsets of the lower 10^{th} and 25^{th} percentiles. This partitioning, while capturing the lower DO events, causes the exclusion of fish interview records where there was no water quality in the lower 10^{th} or 25^{th} percentiles.

Conclusions and Recommendations

Increasingly degraded DO conditions, caused by anthropogenic sources, in the Chesapeake Bay over the past century have been negatively impacting human uses of the Bay, including recreational striped bass fishing. For recreational striped bass fishing these losses impact where, when, and if fishermen will catch a fish. Development of a human-use indicator model that describes the effect of water quality on recreational striped bass catch in the Chesapeake Bay allows for the more precise quantification of low DO's effect on fish catch. These improved models determine optimum DO for striped bass recreational catch in the Chesapeake to be in the range of 8-9 mg/L. Positive relationships between increased DO and catch are seen in the majority of statistical analysis for the Chesapeake. The predictive capability of the model also allows coastal managers to better determine where resources, further research, and remediation will have the greatest returns.

For the series of non-parametric analysis 55% followed expected trends of increasing catch with increasing DO while 10% had inverse relationships (Table 8). The remaining 35% of analysis had unclear results. According to the Poisson distribution multivariate model when DO is increased from 2 to 5 mg/L DO over the whole Chesapeake Bay there is a corresponding increase in striped bass catch of 149.4% (Table 7).

Even though interpolated water quality did not improve results in this study it is still recommended that for future assessments of this kind that they are used. This is because for other species, geographic locations, or time periods interpolated data may improve results. Also, under different circumstances interpolated data may actually perform better than point data.

A further recommendation for the non-parametric portion of this assessment and future assessments of this type would be to take a further step and create 95% confidence intervals for the resulting correspondence analysis plots. The addition of the 95% confidence intervals would allow for further interpretation of the correspondence analysis.

Although this study demonstrates well that degraded DO conditions impair recreational striped bass catch, there are many other human uses that can be affected by degraded water quality. Understanding the relationships between human uses such as swimming, boating, and fishing for fish species other than striped bass are also important and should be studied in future assessments. Improved modeling of multiple human uses of coastal waters will allow for improved management and policy, as well as making estuarine restoration a priority.

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